EVALUATING THE SUSTAINABILITY OF DOUBLE - CROPPING ROTATIONS WITH PENNYCRESS (*Thlaspi arvense*)

A Thesis
SUBMITTED TO THE FACULTY OF
THE UNIVERSITY OF MINNESOTA
BY

Sarah A. Moore

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

M. Scott Wells, Roger L. Becker

December 2019

© Sarah Ann Moore 2019

Dedication

To my dad, whose support got me through the toughest parts of both of my degrees, and who has always had unwavering faith in my ability to succeed.

Abstract

Pennycress (*Thlaspi arvense* L.) is an emerging winter annual cash cover crop that can help address environmental concerns with summer annual cropping systems while also providing additional income as an industrial feedstock. Cropping systems research has mainly focused on incorporating pennycress into the corn – soybean rotation that dominates the upper Midwest. However, research into double-cropping systems with specialty crops is lacking. The purpose of this thesis is to assess the environmental and economic feasibility of a variety of specialty crops following pennycress; determine the effects of sweetcorn nitrogen fertilization on following pennycress yields; and quantify the ability of pennycress to reduce residual inorganic soil nitrogen.

TABLE OF CONTENTS

LIST OF TABLES iv
LIST OF FIGURES v
CHAPTER 1 AGRICULTURAL LAND USE IN THE UPPER MIDWEST: A CASE FOR DOUBLE-CROPPING WITH PENNYCRESS 1
1.1 Introduction 1
1.2 Nitrogen and Land Use Change 2
1.3 Living Cover 3
1.4 Cover Crops 4
1.5 Introducing Pennycress 5
1.6 Double-Cropping 7
1.7 Double-Cropping and Adapting to Climate Change 8
1.8 Multi-Cropping with Pennycress 9
1.9 Potential Summer Annuals 11
1.10 Summary and Future Research 16
CHAPTER 2 DOUBLE-CROPPING SHORT-SEASON HIGH-VALUE SUMMER ANNUALS WITH PENNYCRESS 18
2.1 Summary 18
2.2 Introduction 19
2.3 Materials and Methods 21
2.4 Results and Discussion 25
2.5 Conclusions 34
CHAPTER 3 EFFECTS OF SWEETCORN NITROGEN FERTILIZATION ON SUBSEQUENT PENNYCRESS YIELDS 35
3.1 Summary 35
3.2 Introduction 36
3.3 Materials and Methods 38
3.4 Results and Discussion 40
3.5 Conclusions 45
REFERENCES 66

LIST OF TABLES

TABLE 1.1 Growth parameters for potential summer annuals to double-crop after pennycress……………………………………………………………………..………...46

TABLE 2.1 Crop management for field trials at Rosemount Research and Outreach Center, Rosemount, MN………………………………………...…………………47

TABLE 2.2 Soil characteristics of Rosemount, MN field sites by year…………………49

TABLE 2.3 Monthly climate data and departure from norms for Rosemount, MN over the 2015-2018 study period…………………………………………………………...50

TABLE 2.4 Studies reporting dry bean yields in the upper Midwest, conducted 1977-2015…………………………………..…………………………….…...52

TABLE 2.5 Average hydrothermal time available to summer annuals following pennycress at four Midwest locations over the past 30 and 10 year periods…………….53

TABLE 2.6 Success rate of summer annuals double-cropped after pennycress at four locations in the upper Midwest estimated using hydrothermal time………………….…54

TABLE 2.7 Table 2.7 Average grain yield by year for summer annuals following pennycress…………………………………………………………………………..…57

TABLE 3.1 Soil characteristics of Rosemount and Waseca, MN field sites by year……58

TABLE 3.2 Monthly climate data and departures from normal for Waseca, MN over the 2017-2018 and 2018-2019 growing seasons…..……………………………………..59

TABLE 3.3 Monthly climate data and departures from normal for Rosemount, MN over the 2017-2018 and 2018-2019 growing seasons…………………………….………...60

TABLE 3.4 Mixed-model analysis of variance of pennycress yield, residual inorganic soil nitrogen at pennycress planting and pennycress harvest, pennycress biomass, and pennycress nitrogen uptake……………………………………………………………61

TABLE 3.5 Residual inorganic soil nitrogen at pennycress planting…………………....62

TABLE 3.6 Residual inorganic soil nitrogen at pennycress harvest by planting treatment………………………………………………………………………………63

Table 3.7 Average biomass, N uptake, and seed yield for pennycress across all environments…………………………………………………………………………..65

LIST OF FIGURES

FIGURE 2.1 Historical HTT for a summer annual following pennycress by location….55

FIGURE 2.2 Net income of cropping system by year…………………………………...56

FIGURE 3.1 Interactive effects of nitrogen treatment and pennycress planting method on mean residual inorganic soil nitrogen at pennycress harvest…………………………64

CHAPTER 1

AGRICULTURAL LAND USE IN THE UPPER MIDWEST: A CASE FOR DOUBLE-CROPPING WITH PENNYCRESS

1.1 Introduction

Current land use practices have resulted in worldwide issues with nitrogen pollution, the major source of which is agriculture. One method to reduce nitrogen pollution is through the implementation of winter annual cover crops. While cover crops can provide a host of ecosystem services, many farmers are reluctant to incorporate them due to high cost and little to no direct return. By utilizing a species that can also be harvested for profit – a cash cover crop – the financial barrier to cover crop adoption may be overcome by creating a double-crop system. Double-cropping, defined as planting two cash crops in succession without overlap, can bring a myriad of environmental benefits to agricultural systems by temporally increasing the amount of living cover and boost revenues by having a second harvestable crop. However, the success of this system hinges on having the right combination of crops and adequate water and growing degree days (GDD) to support both crops to maturity. Currently, farmers in the Upper Midwest have few options for a winter annual, as many crops that are successful further south in the United States are not cold-tolerant enough to reliably survive the winter. Pennycress is a crop currently in development that can serve as a new option for a winter annual double-crop. It has a short life-cycle, is winter-hardy, and can be harvested for its oil-rich seeds. Traditional grain crops like full-season soybean and corn may not reliably reach maturity if planted after pennycress due to lack of thermal growing units in the remainder of the season. However, there are a variety of alternative short-season summer annuals that could work well in a rotation with pennycress. If these systems prove to be both environmentally and economically viable, they will provide a new, more sustainable cropping system for farmers in northern climates.

1.2 Nitrogen and Land Use Change

Nutrient pollution is a growing issue worldwide, particularly as it affects water quality (Spalding and Exner 1993). In a global nitrogen assessment by Liu et al. (2011), total nitrogen input for croplands was calculated at 136.6 million MT during the year 2010, of which only 55% was taken up by crops and crop residues, with nearly 40% being lost from agroecosystems. The nitrogen lost from agricultural systems can be accumulated in other ecosystems, particularly aquatic systems, and become a pollutant. In the U.S. alone, the cost to mitigate these issues is estimated in the tens of billions of dollars (Syswerda et al. 2012). The majority of this contamination comes in the form of runoff and leaching from agricultural fields (Staver and Brinsfield 1998). Nitrogen losses from agriculture have been exacerbated over the years due to increased use of tile drainage, elevated fertilizer use as a result of the expansion and intensification of corn production, and increased frequency of high intensity precipitation (David et al. 2013; Van Meter et al. 2016). Tile drainage was first implemented in the 1830's and is now utilized in at least 25% of agricultural land. Implemented to prevent waterlogging and dry out fields for spring planting, tile drainage also increases the transport of water-soluble nitrogen off-site (Sands 2018). Corn requires large quantities of N fertilization, approximately 200 kg N ha^{-1} (Kaiser et al. 2018), and has a low nitrogen use efficiency, meaning much of the nitrogen applied is not taken up by the plant and is susceptible to offsite transport (Wortman et al. 2011). So, as corn production expands and intensifies, the amount of nitrogen lost from these systems increases. Additionally, climate change is causing an increase in the frequency and intensity of rain events (Seeley 2015), which exacerbates the loss of water-soluble nitrogen from agricultural systems.

Over the past several decades the agricultural landscape in the Midwest has changed from a diversified mosaic of crops to a primarily corn (*Zea mays*) – soybean (*Glycine max*) rotation as a result of technological improvements in genetics and agronomics, highly productive soils, and evolving market forces (Aguilar et al. 2015; Farris et al. 1977). The U.S. ethanol policy and increased soybean demand from China had a particularly heavy influence, causing an increase in corn and soybean acreage at the expense of small grains and other diversified systems (Aguilar et al. 2015; Grassini et al.

2014; Jekanowski and Vocke 2013). Crop-specific herbicides and pesticides, and more efficient machinery are all examples of advances in technology for corn-soybean systems that have helped increase their adoption. New, high-yielding and pest-resistant seed varieties have also helped, alongside agronomic improvements in tillage and irrigation management (USDA-ERS 2019). In 2018, 71% of the total cropland in the upper Midwest was planted to corn and soybean, a system solely consisting of summer annuals (USDA-NASS CDL, 2018).

In humid temperate climates, the majority of nitrate leaching occurs during the fall and spring due to increased rainfall, which coincides with the shoulder season – the period of time when the main crop is not growing – in summer annual cropping systems (Salmerón et al. 2010). Throughout much of the United States, agricultural land is left bare during the shoulder season from November through May, exacerbating nitrogen loss (Randall et al. 2003; Strock et al. 2004). Regional responses by lawmakers to this environmental issue have included strategic planning initiatives such as the Minnesota Nutrient Reduction Strategy (2014). This program identified three major ways to reduce the amount of nitrogen entering waterways from agricultural systems: fertilizer efficiency, management of tile drainage systems, and increasing vegetative cover. Increasing vegetative, or living, cover is highlighted as having the greatest potential impact on reducing nitrogen pollution due to the variety of ways it can be implemented (MPCA 2014).

1.3 Living Cover

Maintaining living cover throughout the year can improve soil health by reducing erosion, improving soil structure, and increasing water infiltration (Blanco-Canqui et al. 2015). Living cover also takes up nutrients through extensive root systems, reducing the amount of valuable nutrients lost to leaching or runoff and thereby potentially reducing fertilizer expenses (Schlapfer and Erickson 2001; Mays et al. 2003; McCracken 1989; Salmerón et al. 2010). Although natural regeneration – the regrowth of weeds and crop volunteers – is not as effective as a designated crop (Premrov et al. 2014), even a weedy cover can reduce nitrate leaching by up to 60% compared to bare ground during the shoulder season (Wortman 2016).

Keeping a designated crop – a species that has been specifically bred for cultivation – on the field year-round also decreases weed establishment through resource competition, potentially reducing herbicide use (Hartwig and Ammon 2002). For example, in the Netherlands fodder radish, winter oilseed rape (*Brassica napus*), and winter rye (*Secale cereale*) reduced weed biomass by 70% in the fall compared to the bare-ground control (Kruidhoff et al. 2008). In another study carried out in southeastern France, white clover (*Trifolium repens*) intercropped with soft winter wheat (*Triticum aestivum*) reduced weed shoot dry matter by 1.4 to 1.8 Mg ha^{-1} compared to mono-cropped wheat (Vrignon-Brenas et al. 2018).

Adding vegetative cover also increases the number of plant species on the landscape and diversifies agricultural systems, which helps to buffer against losses due to pests, disease, and extreme weather events (Kazemi et al. 2018; Lin 2011; Altieri 1999, 2015; Andow 1983; Holt-Giménez 2002). In one study, decreased biodiversity caused by an increase in soybean monocultures in the Midwest resulted in a 24% reduction of biocontrol, which translated to an estimated $58 million per year loss to producers in the form of reduced yield and increased pesticide application (Landis et al. 2008). While there are many methods to increase living cover, there has been a great deal of attention focused on cover crops, as they do not take land out of production and can potentially provide other agronomic benefits, such as forage production and nitrogen credits (Noland et al. 2018; Myers and Watts 2015; Snapp et al. 2005).

1.4 Cover Crops

Since the 1930s, research has shown the capabilities of cover crops to reduce nutrient leaching in agricultural fields, increase soil health and pollinator resources, suppress weeds, slow erosion, and potentially control pests (Mays et.al. 2003; SARE 2012). As a result, cover crops can increase the environmental sustainability of agricultural lands as well as provide secondary on-farm benefits. For example, in no-till research plots with cover crops and long rotations, researcher Sharad Phatak from the University of Georgia has not had to use insecticides for many years on peanuts, cotton, nor vegetables (SARE 2012). In a study by Mallinger et al. (2019) in the Northern Great Plains, pollinators visited all cover crop plantings, but most heavily attended plantings

including buckwheat (*Fagopyrum esculentum*) – a plant with heavy flower set – though each pollinator type had a preference of which cover crop they visited most frequently. Noland et al. (2018) found that a variety of different species of cover crops planted into standing corn reduced soil nitrate compared to no cover controls as long as aboveground cover crop spring biomass exceeded 390 kg ha^{-1}.

Cover crops can be incorporated in a number of ways, but in northern climates the most effective way to reduce nitrogen loss is through the use of winter annual cover crops. These crops are winter hardy, and thus are able to uptake nitrogen in both the fall and the spring. The dominance of winter-active genotypes both within and across species has been corroborated by a number of different studies (Malcolm et al. 2014; 2015; McLenaghen et al. 1996; Teixeira et al. 2016; Valkama et al. 2015; Noland et al. 2018). Compared to bare soil, winter annual cover crops can reduce nitrogen leaching 80 to 95% depending on the species and rainfall conditions (Staver and Brinsfield 1998; Meisinger and Ricigliano 2017), twice as much as autumn cover crops (Thomsen and Hansen 2014). Additionally, many of these crops bloom early in the spring, providing resources to pollinators (Eberle et al. 2015). Winter annual cover crops can fill the gap between summer annual cropping cycles to maintain a living cover on the landscape (Premrov et al. 2014).

Although the benefits of cover crops are well-documented, only 2.3% of cropland in the Midwest utilizes them (Roesch-McNally et al. 2017; CTIC 2017). According to focus-group research conducted in Iowa, producers felt that more economic incentives and more diverse markets are necessary to increase cover crop adoption (Roesch-McNally et al. 2017). Implementing a cash cover crop, which provides direct economic returns in addition to ecosystem services, may be an answer.

1.5 Introducing Pennycress

Pennycress (*Thlaspi arvense*) is a winter annual cash cover crop that is currently under development. Native to Eurasia, pennycress is winter-hardy brassica with a T_{base} of -2.5°C and recorded survival down to -30°C (Fan et al. 2013; Royo-Esnal et al. 2015; Sedbrook et al. 2014). Planted in the early fall and harvested in the late spring/early summer, pennycress has a relatively short life-cycle (80-120 days) which makes it

appealing for incorporation into established summer annual cropping systems (Phippen and Phippen 2012; Sedbrook et al. 2014; Dose et al. 2017; Cubins 2019; Groeneveld and Klein 2014). Additionally, it maximizes seed yields with a split application of only 56 kg N ha^{-1} (28 kg N ha^{-1} in both the fall and spring) (Rukavina et al. 2011).

Pennycress provides a host of ecosystem services, making it an excellent addition to cropping systems. Work by Eberle et al. (2015) in the upper Midwest and by Groeneveld and Klein (2014) in Germany demonstrated that the mass flowering of pennycress early in the spring serves as a forage resource for pollinators when little else on the landscape is in bloom. Additional research shows that, when double-cropped with corn, pennycress increases diversity of ground-beetles and spiders (Groeneveld and Klein 2014; Groeneveld et al. 2015). Pennycress also serves as a weed suppressor by providing competition though sustained ground cover, likely aided by the allelopathic compound sinigrin (Johnson et al. 2015). Perhaps most importantly, pennycress has also been shown to significantly decrease nitrogen leaching and runoff. In a double-cropped system with soybean, pennycress significantly reduced nitrogen in both the soil and the leachate at all sample depths to 60 cm compared with a mono-cropped tilled system (Weyers et al. 2019; Thom et al. 2018; Johnson et al. 2017), sequestering 35 to 40 kg N ha^{-1} by mid-spring, which is comparable to winter rye (Ott 2018). In another study, pennycress and its relative camelina (*Camelina sativa*) both significantly reduced nutrient runoff compared to tilled fallow, no-till fallow, and no-till radish and rye winter systems (Weyers et al. 2019).

Unlike many other fall planted cover crops, pennycress survives the winter and has a very short growing season, making it amenable to farmers to grow the crop to maturity rather than incorporate or mow it. As a result, it can be harvested as a cash crop rather than incorporated or terminated as a cover crop. Related to canola, pennycress has seeds rich in oil (24 to 39% wt/wt) (Sedbrook et al. 2014). Most pennycress accessions have a fatty acid profile of 11% oleic, 20% linoleic, 13% linolenic, 10% eicosenoic, and 33% erucic acid, which makes the oil unsuitable for human consumption but excellent for industrial applications such as biofuels, bioplastics, and industrial lubricants (Sedbrook et al. 2014; Fan et al. 2013; Eberle et al. 2015; Sindelar and Schmer 2017; Cermak et al.

2013, Evangelista et al. 2017). However, current genetic research has discovered a mutant population of pennycress with food-grade oil that has a profile similar to that of canola (Chopra et al. 2019). In addition to the oil, the remaining seedmeal after pressing has uses as a biofumigant (Johnson et al. 2015; Vaughn et al. 2005, 2006; Isbell 2009), high-protein feedstuffs (Sedbrook et al. 2014; Fan et al. 2013; Sindelar et al. 2017; Hojilla-Evangelista et al. 2013 and Selling et al. 2013), and fuel (Fan et al. 2013). The combination of pennycress's cold tolerance, environmental services, and valuable seed oil and presscake make it a promising winter annual for incorporation into summer annual rotations in the upper Midwest, where options for winter annuals are limited.

1.6 Double-Cropping

Double-cropping, or sequential multi-cropping, is an example of temporal intensification, whereby two crops are grown in succession in the same field in the same year, with no overlap in their lifecycles (Berti et al. 2015; Andrews and Kassam 1976). Double-cropping allows for an increase in total biomass production and creates the potential for additional income through the harvest of a second crop (Berti et al. 2015; Johnson et al. 2015). In a study by Heggenstaller et al., total annual dry matter production was 25% higher in a maize-triticale system compared with a maize monocrop (2008). By having two crops growing in succession, double-cropping creates an extended period of living cover on the landscape, providing many of the same environmental benefits as incorporating a cover crop into rotations (Johnson et al. 2017; Weyers et al. 2019). For example, in a rye - corn silage double-cropping system, Krueger et al. (2012) found an increase in soil organic carbon (8%), a decrease in soil nitrogen loading (100%) and concentrations of N in soil solution (71%), and an increase in ground-cover (30%) compared to mono-cropped corn silage over a three year period.

The most common double-crop rotation in the United States is a winter cereal followed by soybean (Berti et al. 2015). Of the winter grains, wheat (*Triticum aestivum*) is by far the most popular, accounting for 72% of the double-crop rotations proceeding soybean nationwide (Borchers et al. 2014). The winter wheat – soybean double-crop can provide a high return on investment, as winter wheat generally yields higher than spring wheat varieties and is easier to manage in the spring than winter barley (*Hordeum*

vulgare) or rye (Seifert and Lobell 2015; SARE 2012; Kantar et al. 2011). However, winter wheat is not as cold-tolerant as rye and exhibits high rates of winter-kill in areas like the upper Midwest. As a result, rye is more commonly grown as the winter annual in northern latitudes of the United States (Fowler 1982; Borchers et al. 2014; Berti et al. 2016). But rye also requires large amounts of water to reach maturity, potentially limiting soil moisture available to the proceeding crop (Kruger et al. 2012).

While double-cropping has many benefits, there are also limitations to the system. Adding a second crop complicates management, which translates into increased resource use (Marra and Carlson 1986; Gesch and Archer 2013). As a result, even if total yield increases compared to a mono-crop system, total economic output may not (Cubins 2019). Since the crops are grown in close succession, they must be chosen to avoid any allelopathic effects, transmission of pests, and competition for resources (Sedbrook et al. 2014; Groeneveld and Klein 2014). The main resources that limit double-cropping success are GDD and soil moisture (Groeneveld and Klein 2014; Berti et al. 2015).

Although double-crop systems can produce a higher total yield than single-crop systems, the process of ensuring both crops reach harvestable maturity may result in a reduced yield for one or both of the crops due to competition for GDD and/or soil moisture (Johnson 1987; Hardman and Gunsolus 2002; Gesch et al. 2014). For example, Gesch et al. (2014) found that soybeans planted after camelina had a lower yield than either soybean planted into standing camelina or full-season mono-cropped soybean, a reduction of 33 to 70% and 25 to 63%, respectively, due to a later planting date and thus reduced GDD. In a study conducted from 2009 to 2014, Martinez-Feria et al. (2016) looked at the effects of rye preceding maize and found that, while a soil water deficit was caused by rye transpiration, maize yield was only negatively affected during drought years. Some farmers will avoid these issues by harvesting one of the crops early for use as a forage, rather than waiting until grain maturity (Borchers et al. 2014; Gesch et al. 2014; LeMahieu and Brinkman 1990).

1.7 Double-Cropping and Adapting to Climate Change

The global climate is changing in a way that increases overall temperatures, changes weather patterns, and causes more extreme weather events (Seeley 2015). In the

upper Midwest, climate change means higher annual precipitation with more extreme and localized rainfalls, higher frequency of high dew points, and an increase in the mean of daily low temperatures (Seeley 2015). These changes will determine the relative success of cropping systems in the region, especially complex systems such as double-cropping that rely heavily on weather and timing. Seifert and Lobell (2015) looked at daily weather and crop phenology to determine the effects of predicted climate change on regional suitability for wheat-soybean double-cropping in the United States and found a 126 to 239% increase in area potentially available to successfully implement this system, due to an increase in temperature in locales previously limited by available GDD.

Double-cropping has a long history, dating back at least as early as 2,600 BCE in the Indus Valley, but was first adopted in the United States in the 1940s and became a widespread practice by the 1970s (Weber 2003; Berti et al. 2015). Currently, the majority of double-cropping in the United States occurs in the East: the Southeast if measuring by total acreage (1.09 billion ha), or the Northeast if measuring by percent of total farm acreage (approximately 10%). Conversely, the Pacific Northwest and the Northern Plains have the lowest total acreage (37,231 ha) and percent of farm acreage (<0.5%) in double-cropping, respectively (Borchers et al. 2014). Seifert and Lobell (2015) suggested that the higher amount of GDD available in the more southern latitudes is what allows double-cropping to be so successful in the Southeast. However, the prevalence of double-cropping in the Northeast suggests that limited GDD can be overcome by using alternative cropping combinations, production practices, or new technologies (Borchers et al. 2014).

1.8 Multi-Cropping with Pennycress

Pennycress is a crop that is still under development due to undesirable wild traits such as silicle shatter and variable germination (Carlson 2018). Nevertheless, preliminary genotypes are being utilized to explore pennycress agronomics. Only one study has looked at the effects of nitrogen fertilization on pennycress yields (Rukavina et al. 2011), and while the nitrogen-sequestering abilities of pennycress have been well-investigated, to date no research has investigated the effects of nitrogen fertilization from a preceding crop (i.e., residual inorganic nitrogen) on pennycress growth and yield.

In the Midwest, optimal planting date is in early September to optimize fall biomass and increase seed yield, as well as allow for earlier harvest to facilitate a successful second crop (Phippen et al. 2010; Gesch et al. 2016; Dose et al. 2017). However, seasonal environmental factors have a strong influence on harvest date. Studies in Illinois where pennycress has access to more GDD earlier in the season allow for harvest in May or early June (Phippen et al. 2010b; Rukavina et al. 2011; Phippen and Phippen 2012), while studies further north in Minnesota and North Dakota cannot be harvested until mid-June or early July (Carr 1993; Eberle et al. 2015; Gesch et al. 2016; Dose et al. 2017; Cubins 2019).

In addition to GDD, several studies showed that pennycress growth and yield is limited by water availability in rainfed systems (Clopton and Triebold 1944; Jonson et al. 2015; Royo-Esnal et al. 2017). Pennycress will not germinate if soil moisture is less than -100 kPa (Baskin and Baskin 1989). A study by Matthies (1990) found that if water is limited, though this threshold was not defined, pennycress is less likely to branch. It is pennycress's ability to branch which is what allows the plant to compensate for low stand densities (Matthies 1990; Dose et al. 2017). Low moisture not only affects seed yield, but oil yield as well. In a study by Dose et al. (2017) pennycress seed oil content ranged from 26% to 36%, with variation in precipitation accounting for 86% of this difference.

Regardless of these limitations, pennycress has been successfully integrated into multi-crop systems with soybean in the upper Midwest. In about half of all studies soybean yield was not significantly reduced by the addition of pennycress (Phippen and Phippen 2012; Johnson et al. 2015; Bishop and Nelson 2019). In the other studies, soybean grain yield was reduced by 18 to 30% when relay- or double-cropped with pennycress due to lack of soil moisture and GDD, but total annual grain yield (pennycress plus soybean) was still 48 to 102% greater than a soybean mono-crop (Cubins 2019**;** Ott et al. 2019; Johnson et al. 2017). So, even though total system yields with a pennycress-soybean double-crop are higher than a soybean mono-crop, environmental factors will determine whether or not the soybean yield will be negatively impacted. Reduced soybean yields can be problematic if the value of soybean grain greatly outweighs the value of pennycress grain.

Past studies by Phippen and Phippen (2012), Johnson et al. (2015, 2017), Bishop and Nelson (2019), Cubins (2019), and Ott et al. (2019) have shown that pennycress can be integrated into a soybean cropping system. However, pennycress-soybean multi-cropping comes with risks, and management to optimize the production of both crops is far from refined. Additionally, only two studies have looked at economics rather than solely total grain or oil yield, with opposing results (Cubins 2019; Ott et al. 2019). Looking at economics is essential because multi-crop systems require additional inputs, which may negate any gains from additional yields. Cubins (2019) found variable but consistently negative net yield performance of pennycress–soybean double-crop systems based on fluctuating pennycress yields, high labor costs, and low soybean yields resulting in net performance ranging from -$240 to -$640 per ha. In contrast a study by Ott et al. (2019) found that pennycress-soybean in a rely-cropped system did not differ significantly in net income from a mono-cropped soy. Without a stable net income, soybean may not be the best summer annual to follow pennycress in a double-crop system.

1.9 Potential Summer Annuals

There are many summer annuals that can be grown after pennycress. In order to optimize success, the summer annual must possess a few key characteristics. First and foremost are the number of days or GDD to maturity. The growing season in the upper Midwest is short compared to the rest of the contiguous US. In Minnesota the growing season lasts only 90 to 160 days (based on frost-free days), depending on the latitude. By allowing pennycress to reach maturity the number of days that can be allocated to the summer annual are significantly reduced (NCDC; Gesch et al. 2015). As a result, only summer annuals that require less than 120 days to maturity, or those that have high freeze-tolerance, such as sunflower (*Helianthus sp.*), should be considered (Berglund 2011). To break pest cycles, the summer crop should not be related to the Brassicaceae family, such as canola (*Brassica napus*) or spring camelina (Sedbrook et al. 2014). Also, to better manage the risks of a double-crop system, summer annuals should either require low inputs to reduce upfront costs or have a high return on investment.

Row-crops harvested for grain are the dominant systems in the Midwest. This review will focus on row-crops as a subset of possible summer annuals to maximize potential adoption of double-crop systems for the Upper Midwest (NASS 2017). Potential summer annual crops include: short-season maturity soybeans (*Glycine max*), dry beans (*Phaseolus vulgaris*), proso millet (*Panicum miliaceum*), grain sorghum (*Sorghum bicolor*), teff (*Eragrostis tef*), buckwheat (*Fagopyrum esculentum*), hemp (*Cannabis sativa*), and sweetcorn (*Zea mays*) (Table 1.1).

1.9.1 Soybeans (*Glycine max*)

Soybeans are a potential candidate as summer annuals to follow pennycress because there are already over 3 billion ha of production in MN (NASS 2017), so incorporating pennycress into these systems would have a large impact on the landscape. Historically it has been a highly profitable crop in the United States thanks to its high-quality protein and oil (USSEC). There is a large range of maturity groups (MGs) in soybean, defined by the number of days required to take the plant from planting to maturity (Mourtzinis et al. 2016). The recommended MG to plant in any area is based on climate and available GDD. In MN the recommended MG for full season varieties is 1.0 to 2.0, or approximately 94 to 106 days to maturity (NDAWN). If planting is delayed until mid-June, it is recommended to use a MG 0.5 less than the full season variety, or 1.0 MG less if planting is delayed until late June (Naeve and Nicolai 2018). As a result, MG 0 varieties, which require about 87 days to reach maturity, are often used in MN if planting is delayed. If planting soybean after pennycress in late June in Minnesota, MG 0.2 – 1.4 (980 – 1,180°C GDD) should be considered (NDAWN). While there has been some research on double-cropping with soybean late in the season, more research is still needed to optimize MG selection in a given region (Kelly 2003). In addition to MG, soybeans can be categorized by their usage: commodity type – used for oil and feed, and specialty or 'food-grade' – used for human consumption. Of the two, food-grade soybeans generally yield less, but have a higher price per weight (Chad SunOpta pers. comm June 2019; Erin Gudul pers. comm. May 2019). Regardless of type, soybeans require between 940 and 1,570 mm of water ha^{-1} yr^{-1} depending on MG, location, and other weather conditions (Channel 2016; Kranz and Specht 2012).

1.9.2 Dry Beans (*Phaseolus vulgaris*)

There is already an established industry of dry bean production in MN, accounting for 10% of total dry bean acreage grown in the United States (NASS). Based on research by North Dakota State University (NDSU) and the University of Minnesota (UMN), dry bean days to maturity can vary from 80 – 105 depending on variety, and GDD to maturity can vary from 840 – 930°C (Endres and Kandel 2016; Helm et al. 1990; Ostdiek 2009). Additionally, a study by NDSU showed that dry bean yields do not differ between planting dates (May 11 to June 18) (Endres and Kandel 2016). However, older studies carried out in North Dakota and Oklahoma in 1992 note yield reductions when dry beans are planted after mid-June, mainly due to drought and heat stress coinciding with emergence or flowering (Russo and Perkins-Veazie 1992). For water use, dry beans require only 360-460mm of soil moisture throughout the season to obtain maximum yields and are extremely sensitive to flooding conditions (Helm et al. 1990). Dry beans are not only defined by variety, but also by market class e.g., black, pinto, kidney, etc. Each of these market classes has different characteristics and thus different uses and different consumer preferences, which effect their marketability and price at the elevator (NASS 2016, 2017, 2018). In Minnesota, the major classes of dry bean are: kidney, black, navy, and pinto – although these have fluctuated over the years (NASS).

1.9.3 Proso Millet (*Panicum miliaceum*)

Most small grains are a good choice for a short-season summer annual, as they mature quickly and generally require very few inputs. Proso millet is one of a variety of different kinds millet grown for human consumption, though in the United States it is grown mainly as livestock feed or birdseed (Berglund 2007). The majority of proso millet production in the US is in the Great Plains as a double crop after winter wheat, preferred for its rapid maturation and shallow root systems that allow for the conservation of subsoil water (Habiyaremye et al. 2017). Maturing in 60 to 90 days or approximately 865°C GDD, this crop germinates best in soil temperatures around 18°C with a recommended planting date in June – perfect for following pennycress (Baltensperger et al. 1995; Burglund 2007). Proso millet also has very low moisture (330 to 360mm) and fertilizer requirements (UVM 2011; Boland 2016; Baltensperger et al. 1995). Proso millet

has high market potential in the United States because it is high in amino acids and protein, easy to digest, gluten-free, and is considered on-par with grain sorghum in terms of feed value (UVM 2011; Boland 2016).

1.9.4 Teff (*Eragrostis tef*)

Teff is a variety of lovegrass that is grown as a staple grain in parts of Africa, though in the United States it has mainly been exploited as a forage (Miller 2014). The demand for nutritious grain options for human consumption in the US is growing, and teff is not only high in iron but is also gluten-free (Stallknecht et al. 1993). While teff is extremely drought tolerant, best grain yields are achieved with 430 to 510mm of rainfall per annum, and it requires little to no fertilizer (Miller 2014; Stallknecht 1997). A warm-season grass, teff germinates best in soils above 18°C and exhibits best growth at air temperatures greater than 27°C (Miller 2014). Other than white or brown seeded, varieties can also be separated into forage and grain types. Grain types generally mature faster and achieve higher grain yields while forage types generally produce more biomass (Cal/West Seed 2017). Depending on variety, teff can reach grain maturity in 90 to 130 days (Stallknecht 1997).

1.9.5 Sorghum (*Sorghum bicolor*)

Another small grain that could potentially fit into the double-cropping window with pennycress is sorghum. Sorghum varieties differ in growth and morphology based on what they have been bred for: forage, syrup, or grain (Gerik et al. 1998). Grain sorghum requires soil temperatures between 16 to 18°C for best emergence and are extremely drought- and flood-tolerant (Carter et al. 2019). Water requirements vary by hybrid and growth stage, but, in general, medium-maturing cultivars require about 450 mm during the growing season to produce a good crop (Assefa et al. 2010). Grain types mature in 90 to120 days depending on variety, with short-season hybrids requiring 1,470°C GDD to reach harvest maturity (Kelley n.d.).

1.9.6 Buckwheat (*Fagopyrum esculentum*)

Buckwheat is a pseudo-grain, a plant that has seeds that are utilized as a grain for human consumption but is not a member of the grass family, that is growing in popularity

as a gluten-free alternative. Buckwheat is native to central Asia and is mainly grown throughout Asia and eastern Europe to be used in products for human consumption (Myers and Meinke 1994). However, in the United States buckwheat is touted as a cover crop that provides appreciable pollinator resources (SARE 2012). This crop requires very few fertilizer inputs, having problems with lodging if soil nitrogen is too high, and only 700°C GDD or 70 to 90 days to reach maturity (Bjorkman 2009). It germinates best around 27°C but is highly adaptable and will still germinate from 7 to 41°C (Berglund 2007a). If planting for grain rather than as a cover or forage, it is recommended to plant later in the summer such that flowering and seed set align with cooler autumn nights (Myers and Meinke 1994). Specific water requirements for buckwheat have not been established, but studies have shown that it thrives in cool, moist conditions, responds favorably to irrigation, and is significantly hindered by drought (Popović et al. 2013; Robinson 1980; Gubbels 1978).

1.9.7 Industrial Hemp (*Cannabis sativa*)

Requiring 90 to 120 days to mature and 1,955°C GDD, industrial hemp is another potential candidate to follow pennycress (GMB; Sikora et al. 2011). Hemp germinates best when planted in soil temperatures between 7 and 10°C and requires only 250 to 300 mm of precipitation (MDA; Bósca and Karus 1998). Hemp seeds, also known as hemp hearts, have a high oil content and have been growing in popularity as a healthy meal additive when dried. As another oilseed, there is an opportunity for farmers to invest in on-site oil processing facilities when grown in rotation with pennycress. Unlike other cannabis varieties, industrial hemp by definition contains less than 0.3% dry weight THC (USDA-NIFA 2018). Once harvested for seed, industrial hemp has additional uses as a sustainable source of fiber (Ingrao et al. 2015). A burgeoning industry, industrial hemp holds great potential for farmers.

1.9.8 Sweetcorn (Zea mays convar. saccharata var. rugosa)

While not a grain crop, sweetcorn is an established industry in the upper Midwest, making it a good candidate for the summer annual in a double-cropping system with a winter annual. Sweetcorn is an extremely short-season crop, as it is harvested green rather than at grain maturity. Depending on the variety, it requires anywhere from 60 to

100 days and 800 to 950°C GDD from planting to harvest (Maynard 2009). Sweetcorn is susceptible to drought, and requires 1,250 to 1,880mm/ha of water for good grain fill (TX A&M Extension n.d.). It is possible to plant pennycress either before or after sweetcorn to meet different management needs. Sweetcorn requires large quantities of N fertilizer, approximately 200 kg N ha^{-1}, in order to achieve high-quality ears (Rosen et al. 2017). Additionally, sweetcorn is harvested as a fresh vegetable rather than at grain maturity, meaning that as much as 34.3% to 50% of the nitrogen applied as fertilizer is not utilized by the plant and is thus susceptible to being transported off-site into the environment (Prasad and Hochmuth 2016; Rosen et al. 2017). The residual soil nitrate from a sweetcorn system is about three times higher than that of grain corn, soybean, and sweetcorn with rye (Rosen et al. 2017). Pennycress planted after sweetcorn could sequester unused nitrogen that would otherwise contaminate surface and groundwater resources.

1.10 Summary and Future Research

Nitrogen loss has been exacerbated through land use changes in agriculture, but the implementation of living cover, such as cover crops, can help to ameliorate the issue. However, adoption of cover crops is low in large part because they do not provide direct revenue. The inclusion of a cash cover crop during the shoulder season to create a double-crop system may be a solution. Double-cropping has brought environmental benefits and extra revenue to farms since 2,600 BCE, though lack of GDD and soil moisture are significant risks especially in the upper Midwest, where GDD are extremely limited. Pennycress is a new option for a winter annual cash cover crop that is winter-hardy in the upper Midwest.

While pennycress can be successfully cropped with soybean, environmental conditions impact grain yield and seed oil content. Data has not been extrapolated across space or time to elucidate how frequently double-crop systems with pennycress would allow for positive yields in our changing climate. Additionally, variation in yield means variation in net return, and as such the system is not always economically viable. Alternatively, there exist a variety of short-season summer annual row-crops that can potentially provide a positive return in a double-crop system with pennycress, though

they have yet to be investigated.

Double-cropping systems with pennycress as the winter annual crop hold great promise in the Upper Midwest thanks to the ability of pennycress to produce both environmental services and economic return, as well as its short time to maturity. However, there are still several questions that need to be answered concerning pennycress agronomics before recommendations can be made, such as pennycress best management practices, economic tradeoffs in pennycress double-crop systems, and environmental risks associated with pennycress double-cropping.

CHAPTER 2

DOUBLE-CROPPING SHORT-SEASON HIGH-VALUE SUMMER ANNUALS WITH PENNYCRESS

2.1 Summary

Double-cropping temporally increases living cover on agricultural landscapes and increases overall productivity. However, increased cost of management and competition for water and growing degree days (GDD) pose risks to the success of double-cropping systems. In the upper Midwest, winter annual options to double-crop are limited, but a new winter annual crop, pennycress (*Thlaspi arvense*) holds promise. In a field study, eight summer annual crops [soybean (*Glycine max*), dry bean (*Phaseolus vulgaris*), proso millet (*Panicum miliaceum*), teff (*Eragrostis tef*), buckwheat (*Fagopyrum esculentum*), sorghum (*Sorghum bicolor*), hemp (*Cannabis sativa*), and sweetcorn (*Zea mays* convar. *saccharata* var. *rugosa*)] were planted after pennycress, harvested at maturity, and the system evaluated for net economic potential. Sorghum did not reach maturity in any of the study years, and soybean maturity groups 0.7 and 1.4 did not reach maturity in 2018. Only the dry bean double-crop had a higher net income than full-season soybean in 2017 and 2018. Excepting animal pests and establishment issues due to poor seedbed preparation in 2018, all other double-crop systems were not economically different than a full-season soybean monocrop. To quantify risk associated with drought and insufficient GDD, annual hydrothermal time (HTT) data for Ames, IA; Morris, MN; Prosper, ND; and Rosemount, MN were compiled across the past 30 years and compared with the average GDD necessary for each of eight potential summer annual crops to reach grain maturity. Only sweetcorn, dry bean, buckwheat, and proso millet reliably reach maturity at all four locations. Prosper and Morris both showed an increase in mean HTT over the past 10 years, indicating that double-cropping options for these more northern sites may be expanding as climate change progresses. The approach demonstrated in this study can help farmers to better understand the climatic and economic risks associated with double-cropping. Based on net income and reliability of harvest, dry bean, proso millet, buckwheat, and sweetcorn could be recommended as summer annuals to follow pennycress in a double-cropping rotation, but further research is needed to optimize profitability.

2.2 Introduction

Double-cropping is a system in which two crops are grown in succession in the same field in the same year, with no overlap in their lifecycles (Berti et al. 2015; Andrews and Kassam 1976). The practice of double-cropping dates back at least as early as 2,600 BCE in the Indus Valley, but was only widely adopted in the United States in the 1970s (Weber 2003; Berti et al. 2015). This temporal intensification creates an extended period of living cover on the landscape, providing many of the same environmental benefits as incorporating a cover crop into rotations (Johnson et al. 2017; Weyers et al. 2019). Double-cropping increases total biomass production and creates the potential for additional income through the harvest of a second crop (Berti et al. 2015; Johnson et al. 2015).

While double-cropping has many benefits, adding a second crop complicates management, which translates into increased costs and competition for resources (Marra and Carlson 1986; Gesch and Archer 2013). The main resources that limit double-cropping success are growing degree days (GDD) and soil moisture (Groeneveld and Klein 2014; Gesch and Johnson 2015). Competition for these resources may result in reduced yield for one or both crops (Johnson 1987; Hardman and Gunsolus 2002; Gesch et al. 2014). Gesch et al. (2014) found that soybeans planted after camelina had lower yields than either soybean planted into standing camelina as a relay-crop (33 to 70%) or full-season mono-cropped soybean (25 to 63%) due to a later planting date and thus reduced GDD. As a result of increased management costs and potentially reduced gross income, increased system yield from growing two crops may not equate to increased economic gains (Cubins 2019).

The most common double-crop rotation in the United States is winter wheat (*Triticum aestivum*) followed by soybean, accounting for 72% of the double-crop rotations with soybean nationwide, or about 2.5 million ha (Berti et al. 2015; Borchers et al. 2014; Borchers and Wallander 2014). However, winter wheat exhibits high rates of winter-kill in the upper Midwest, and as a result rye is more commonly grown as the winter annual (Fowler 1982; Borchers et al. 2014; Berti et al. 2016). However, rye grain does not mature until August in the upper Midwest (NASS 1997), leaving little time and

GDD for a second crop. Some farmers will avoid this issue by harvesting rye early as a forage (Borchers et al. 2014; Gesch et al. 2014; LeMahieu and Brinkman 1990). With rye as the only grain that reliably survives the winter in the upper Midwest, farmer's options for winter annuals to double crop are limited.

Pennycress (*Thlaspi arvense*) is an oilseed crop that is currently under development as a new winter annual crop option for Midwestern growers. It is extremely cold-hardy with a base growing temperature (T_{base}) of -2.5°C and recorded survival down to -30°C (Royo-Esnal et al. 2015). A Brassicaceae related to canola, pennycress produces seeds with 24 to 39% oil by weight (Sedbrook et al. 2014; Evangelista et al. 2012) that has potential uses as a biofuel, industrial lubricant, and component of biodegradable plastics (Sindelar and Schmer 2017; Eberle et al. 2015; Sedbrook et al. 2014; Fan et al. 2013; Cermak et al. 2013).

In the upper Midwest pennycress is harvested in mid-June or early July (Carr 1993; Eberle et al. 2015; Gesch et al. 2016; Dose et al. 2017; Cubins 2019) and requires little to no additional fertilization to thrive (Rukavina et al. 2011); characteristics ideal for a winter annual in a double-crop system. Previous research shows that pennycress can be successfully relay- and double-cropped with soybean in the upper Midwest, but whether or not the yield of the subsequent soybean crop is negatively impacted varies by environment and pennycress harvest date (Johnson et al. 2015; 2017; Phippen and Phippen 2012; Cubins 2019). If full-season soybean, the dominant summer annual in the upper Midwest alongside grain corn, does not reliably have enough GDD or soil moisture to maintain yields when planted after pennycress, then alternative short-season, fast-growing summer annuals may be able to fill this gap (Gesch and Archer 2013). However, no research has been published on this topic.

Double-cropping relies heavily on timing rotations with weather patterns and the availability of GDD. As the global climate continues to change, so too will the local success of double-cropping systems. In the upper Midwest, climate change means higher annual precipitation with more extreme and localized rainfalls, higher frequency of high dew points, and an increase in the mean of daily low temperatures (Seeley 2015). Seifert and Lobell (2015) suggest that double-cropping success is entirely due to abundance of

GDD, and that the regional suitability for double-cropping will expand northwards with this climatic warming. However, the prevalence of double-cropping systems in the Northeastern United States shows that limited GDD can be overcome by using alternative cropping combinations, production practices, or new technologies (Borchers et al. 2014).

To investigate potential summer annuals to double-crop with pennycress, 16 summer annual crop varieties were planted after pennycress harvest at the Rosemount Research and Outreach Center in MN from 2016-2018 (Table 2.1). The objectives of this study were to 1) analyze historical climatic trends across a range of environments to determine how frequently the environmental conditions are met to allow double-cropping with pennycress to be successful; and 2) assess the economic viability of a variety of pennycress – summer-annual double-cropping systems compared with traditional mono-cropped soybean systems.

2.3 Materials and Methods

2.3.1 Field Studies

Studies were carried out during the 2015-2018 growing seasons at the Rosemount Research and Outreach Center (RROC) located in Rosemount, MN 44°42’36”N 93°04’19”W on an Ostrander loam in 2015-2016, an Urban land-Waukegan complex in 2016-2017, and a Waukegan silt loam soil in 2017-2018 (Table 2.2). Precipitation and air temperature data (Table 2.3) were obtained from the NOAA reporting weather station at RROC. Spring wheat (*Triticum aestivum* L.) was grown the summer prior to pennycress planting in 2015 and 2017, and alfalfa (*Medicago sativa* L.) preceded pennycress in 2016.

Pennycress (*Thlaspi arvense* L., “MN106”) was broadcast planted on a field scale in mid-September with a Brillion seeder (Landoll Corp., Marysville, KS) after primary and secondary tillage. No fertilizer was applied to pennycress. In mid-June mature pennycress was direct-combined using a Wintersteiger Plot Master (Wintersteiger Inc., Salt Lake City, UT) in 2016 and was swathed one week prior to combining in 2017 to obtain seed yields. Due to wet field conditions and mechanical issues with the combine, pennycress was hand-harvested in 2018 before being mowed.

All summer annual plots were fertilized pre-plant with a broadcast application of fertilizer at 45 kg N ha^{-1} in the form of urea and treated with glyphosate applied post-

emergent as a burn-down (2.2 kg ae ha^{-1}). Herbicide treatments varied between study years (Table 2.1). Each summer annual crop or variety served as a treatment and were established no-till into pennycress stubble in a randomized complete block design with four replications. The 2016 study had a total of 13 treatments, in 2017 two additional dry bean varieties were added for a total of 15 treatments, and industrial hemp was added in 2018 for a total of 16 treatments (Table 2.1). Grain treatments were planted with a no-till drill (Truax Co. Inc., New Hope, MN) in 3 x 9 m plots on 20 cm row spacing at a depth of 2.5 cm with the exception of teff, which was planted at a depth of 0.6 cm. Legume and sweetcorn treatments were established with a six-row planter (John Deere 7100 MaxEmerge, Deere and Co., Miline, IL) in 4.6 x 9 m plots at a depth of 3.8 cm. Sweetcorn was planted with 76 cm row spacing, while soybeans and dry beans were planted with 38 cm row spacing using two passes of the planter. Sweetcorn was side-dressed by hand with an additional 32 kg N ha^{-1} urea at the V4 stage. Baseline soil samples were collected prior to summer annual planting and again at summer annual harvest. After summer annuals were planted, soil moisture, ground cover, leaf-area-index (LAI), and growth-staging were evaluated on a weekly basis to monitor crop health.

All summer annuals except for sweetcorn were harvested once they reached maturity and placed into a 35°C oven and dried to a constant weight. Crops were then threshed either by hand or using a Wintersteiger LD 350. Yields were adjusted to 13% moisture and extrapolated to kg ha^{-1}. Sweetcorn was measured as fresh weight, yield extrapolated to kg ha^{-1}.

2.3.2 Economics

Gross income was calculated for each crop using prices from the National Agricultural Statistics Service (NASS 2016, 2017, 2018) and independent grain elevators where NASS did not have data. Prices for rapeseed were used as a proxy for pennycress grain prices. Net income was calculated by subtracting costs for fuel, lubricants, repairs and maintenance, labor, and power and implement depreciation for fertilizer application, weed control, and use of a no-till drill, boom sprayer, combine, and grain cart, as well as seed cost from yield income (Cubins 2019). Land rental and crop-specific costs such as certification for hemp growing were not included in this analysis. Pennycress net income

was added to all crops to account for the additional costs and incomes associated with a double-crop system, and all double-crop systems were compared to the average net income for full-season conventional soybeans in Dakota County in the same year using a Dunnett's test ($P<0.05$). Crops that did not reach maturity were not included in the analysis.

2.3.3 Environmental Data

Specific environmental conditions are necessary for double-crop systems to be successful. To estimate how often these conditions are met, soil moisture potential (SMP) and growing degree days (GDD) were calculated for each pennycress – summer annual cropping cycle during the past 30 years at the study site as well as for Morris, MN (MN 45°41'12"N 95°48'12"W), Ames, IA (42°1'15"N 93°46'27"W) and Prosper, ND (47°0'5"N 97°6'46"W) to extrapolate results across the upper Midwest. The SMP at 5cm depth was calculated using the software STM^2 (Soil Temperature and Moisture Model, USDA-ARS Java program). Inputs included daily maximum and minimum air temperatures and precipitation recorded by the weather station on-site, as well as site-specific soil characteristics and day of year (DOY). Where data was missing from the on-site weather station, the average readings from nearby stations on that day were used as a proxy.

Pennycress base and ceiling temperatures have only been explored using soil temperatures, so GDD for pennycress was calculated using on-site soil temperatures, while summer annual GDD were calculated traditionally using air temperatures (Royo-Esnal et al. 2015). GDD were calculated using the formula:

$$GDD = \sum \frac{(T_{max} - T_{min})}{2} - T_{base}$$

Condition 1: if $T_{min} < T_{base}$ then $GDD = \sum \frac{(T_{max} - T_{base})}{2} - T_{base}$

Condition 2: if $T_{max} > T_{ceiling}$ then $GDD = \sum \frac{(T_{ceiling} - T_{min})}{2} - T_{base}$

Condition 3: if $T_{max} < T_{base}$ and $T_{min} < T_{base}$ then $GDD = 0$

T_{min} = minimum daily temperature
T_{max} = maximum daily temperature
T_{base} = base temperature at which a plant can begin growing
$T_{ceiling}$ = temperature at which growth is retarded due to heat damage

GDD for pennycress was calculated with a T_{base} of -2.5°C and $T_{ceiling}$ of 25°C, and GDD for summer annuals was calculated with a T_{base} of 10°C and $T_{ceiling}$ of 25°C (Royo-Esnal et al. 2015). GDD using soil temperatures may also be referred to as thermal time (TT), and SMP may also be referred to as hydro time (HT). These two measurements were used to calculate hydrothermal time (HTT) using the formula (Roman et al. 2000):

$$HTT = \sum HT \, x \, TT \qquad \text{where} \quad HT=1 \quad \text{if} \quad \psi > \psi_b$$

ψ = average daily SMP
ψ_b = base water potential

For this paper the permanent wilting point for soil, -1500 kPa, was used as ψ_b.

Pennycress matures around 2,190°C GDD (Cubins 2019; Table 1.1). For each of the 30 years at the abovementioned four locations, pennycress planting was set at a standard Sept. 15, based on previous studies by Dose et al. (2017) and Phippen et al. (2010b) for optimal planting date. The number of GDD from that point onwards was calculated, and the date that 2,190°C GDD was reached was treated as the day pennycress could be harvested in a given year, and the first date thereafter as the first day a summer annual could be planted. The Rosemount location did not have soil temperature data from 1988-2003, so the pennycress growth period was calculated using soil temperature estimates produced by the STM^2 software. Data for three years with measured soil temperatures were analyzed with STM^2 to check if the software overestimated GDD accumulation, and the results did not differ.

The period which a summer annual could potentially grow was calculated from the day after hypothetical pennycress harvest until the first killing frost (-2°C). The total accumulated HTT during this period was compared to the average number of GDD necessary to take each of the crops in this experiment to maturity. If the required GDD for a crop fell within or below one standard error of the mean at a given location, it was defined as reliably reaching maturity.

2.4 Results and Discussion

2.4.1 Climate Trends

The average number of HTT available for a summer annual to follow pennycress varied between locations, with the two more southern locations (Rosemount and Ames) having 22% to 35% more HTT than the two northern locations (Morris and Prosper) (Figure 2.1). The northernmost locations in this analysis experienced a heating trend over the last ten years compared to the last 30 years, indicating that these locations may be increasingly favorable for double-cropping. Seifert and Lobell (2015) outlined mean temperatures as the limiting factor to double-cropping, and as global temperatures continue to rise the areas amenable to double-cropping increase. The global warming trend is more pronounced in mid- to high-latitudes, with temperatures in Canada's prairie provinces rising by 1.6°C since 1895 (Sauchyn et al. 2008) compared with the global average of 1.1°C (IPCC 2018). In addition, winter and spring warming has increased at these mid- to high- latitudes more rapidly than summer warming, decreasing overall seasonal temperature fluxes (Solomon et al. 2007). This northward shift of heat units translates into a northward shift of areas suitable for double-cropping, particularly in Minnesota (Lant et al. 2016).

Climate prediction models for Minnesota calculate an overall warming trend with average temperatures rising 4 to 5°C by the end of the century (Lucash et al. 2017; Seeley 2015; CREST 2011; Galatowitsch et al. 2009). Rosemount, MN is no exception to the forecasted trend, and is projected to have a warmer and wetter climate similar to western Iowa by the middle-end of the century (Byun and Hamlet 2018; CREST 2011). However, in the past 10 years Rosemount has experienced a decrease in average yearly GDD, as has Ames, IA, though less drastically, with a -4.5% and -1.2% reduction, respectively. Model predictions of average temperatures look at the next 50 to 150 years, so the past decade at Rosemount may be an example of short-term climate variability, not indicative of long-term climate change trends (Klink et al. 2013). As the climate continues to change, the approach used in this paper may be useful for vetting other double-cropping systems across a variety of climates.

2.4.2 Pennycress

Seed yield was low in all three years of the trial, averaging 1,028 kg ha^{-1}, 1,028 kg ha^{-1}, and 617 kg ha^{-1} in 2016, 2017, and 2018 respectively. In all years of the study, heavy rains occurred just before pennycress reached physiological maturity with 79, 51, and 132 mm of precipitation in the two weeks prior to pennycress harvest in 2016, 2017, and 2018, respectively (Table 2.3), with a severe downpour in 2018 that accumulated 119 mm of precipitation over the course of five days, exacerbating yield lost to shatter. The pennycress used in this trial is a wild accession that still exhibits weedy characteristics, such as dormancy and seed shatter (Sedbrook et al. 2014). In one study by Cubins (2019), seed lost to shatter accounted for up to 70% of the total yield, while Carlson (2018) found seed loss from shatter equivalent to 300 times the seeding rate. As a result, seed yields can be highly variable. Pennycress seed yields up to 2,500 kg ha^{-1} are possible (Cubins 2019, Johnson et al. 2017), but as a result of shatter realized yields from 400-900 kg ha^{-1} in the upper Midwest are common (Cubins 2019). Reducing pennycress seed lost to shatter is a major area of improvement that is needed in order to make this system economically valuable. If yields can be stabilized in the upper range of currently attainable yields, pennycress has the potential to add a net worth upwards of $800 ha^{-1} to double cropping systems based on estimated yields of 2,000 kg ha^{-1}.

The calculations used in this study (Section 2.3.2) indicate yields of 607 to 827 kg ha^{-1} are needed to break even, depending on the market price, which were attained in all years of the study. However, these calculations used industrial rapeseed as a proxy for pennycress income pricing, which is about $0.10 to kg^{-1} greater than the Agricultural Marketing Resource Center's (AMRC) (2018) estimate of pennycress seed value. Cubins (2019) postulated 1,684 kg ha^{-1} as the minimum yield for pennycress profitability, while Markel et al. (2018) calculated 550 kg ha^{-1} as the breakeven yield using AMRC's estimate of $0.33 kg^{-1}. Each of these studies used different inputs for income and expenses and were calculated for different regions of the US, resulting in the large variation between estimates. Additionally, none of these studies, including ours, account for the potential additional income from pennycress seedmeal, which can yield up to 1,460 kg ha^{-1} with 26% protein (Mitich 1996; Hojilla-Evangelista 2013). In the future it

would be beneficial to have an online calculator such that each producer can use inputs and outputs specific to their operation.

2.4.3 Dry Bean

Net income from double-cropping all dry bean varieties was consistently greater than a conventional full-season soybean mono-crop (Figure 2.2), as dry beans had a higher yield and received double the price per weight of soybeans (Table 2.7; NASS 2016, 2017, 2018). In addition, 2017 was a bumper year, in which dry bean yields can be up to 2.5 times greater than in a normal year (Table 2.7). In the upper Midwest, dry bean yields average 2,400 kg ha^{-1}, and the 2017 dry bean yields in this study averaged 4,900 kg ha^{-1} (Table 2.4). Alfalfa, which can add substantial nitrogen credits to a field, preceded the 2017 study, and may be the reason for this boost in yields (Yost et al. 2011). No other studies have looked at dry bean after pennycress, but Evans and Lawley (2016) found that both dry bean planted as a double crop after rye incorporation and dry bean planted as a relay crop before mowing rye had reduced yields compared to dry beans planted after fallow or winter killed oats and barley. The main reason for the difference in performance of dry bean after the other crops was due to competition for resources, as rye produces large quantities of biomass, while both other crops were winter killed. Pennycress produces little biomass compared to rye, and the positive performance of dry beans in this study suggest that there are no negative effects of double-cropping pennycress before dry beans. Not only is dry bean a highly profitable crop, but will also reliably reach maturity at all locations in the study (Figure 2.1). Dry bean is an excellent choice for a summer annual to follow pennycress.

2.4.4 Soybean

When double-cropped soybean varieties reached maturity, net income for the system was not different from conventional full-season soybean mono-crop (Figure 2.2). Previous work on the economics of pennycress – soybean systems is conflicting. Ott et al. (2018) also found no difference in income between a pennycress – soybean system and mono-cropped soybean, while Cubins (2018) found a consistently negative income for pennycress-soybean systems. Cubins (2018) had low soybean yields, less than half of what was attained in our study (Table 2.7) and used maturity group (MG) 1.1 and MG 1.9

soybean in a double-crop system, while Ott et al. (2018) used 0.1, 0.9, and 1.0 MG soybeans in a relay-crop. By relay-cropping Ott et al. planted soybeans into standing pennycress, thus increasing the amount of GDD the soybean plants had access to, suggesting that availability of GDD and shorter MG's appropriate for the region are essential to double-cropped soybean profitability.

Since soybean across maturity groups have differing GDD requirements to reach physiological maturity, different MG's are recommended depending on the region (NDAWN). Soybeans within MG 0.2 – MG 1.4 would reliably reach maturity in Ames and Rosemount based on 30 year means (Figure 2.1). However, in the past 10 years MG 1.4 soybeans would have only reached maturity twice at Rosemount due to insufficient GDD. In the first two years of the field study, the first killing frost came much later than normal for the area, which allowed the longer season soybeans to reach harvest maturity (USDC- NOAA/NCDC 2013). However, in 2018 the first frost came on October 18th and the MG 1.4 and MG 0.7 soybeans did not reach harvest maturity, and MG 0.3 soybean yields were negatively impacted (Figure 2.2). Shorter-season MG's are recommended if planting later in the season, as after pennycress, due to the risk of frost and limited GDD (Naeve and Nicolai 2018). Soybeans in this study ranged in maturity group from MG 0.2 – MG 1.4, none of which would reliably reach maturity if planted at Morris or Prosper due to consistently low HTT (Figure 2.1). An even shorter-season MG could fit into a rotation after pennycress temporally, however shorter season soybeans tend to have lower yield potential than longer season soybeans, limiting potential profitability (Hardman and Gunsolus 2002).

Further research is needed to match the appropriate soybean MG for planting as a double-crop after pennycress in each region. The methods used in this study for estimating HTT available to a summer annual after pennycress is a useful tool that can augment the need for multi-site field studies. Until appropriate MGs are defined, soybean cannot be considered a reliable summer annual to plant after pennycress.

2.4.5 Teff

Due to lack of threshing equipment teff grain was not collected in 2016, and in 2018 all treatments of teff had uneven establishment, likely due to poor seed-to-soil

contact at planting (Stallknecht et al. 1993). Teff for grain can be reliably grown to maturity at Rosemount and Ames (Figure 2.1), though in this study forage varieties of teff were planted rather than grain varieties, resulting in yields about 20% short of what is considered commercially viable (Table 2.7, Daniel La Faver pers. comm. June 2019) hence the low net income in 2017 and negative net income in 2018 (Figure 2.2). There exists a wide variety of ecotypes of teff, and there is ongoing breeding work to capitalize on the recently sequenced genome to advance climate-specific genotypes to increase seed yield (VanBuren et al. 2019). If repeated, newly available grain varieties should be utilized as summer annuals to follow pennycress. However, if teff is grown outside of a vertically integrated system that has certified the grain as gluten free and organic, a farmer can only make about \$0.46 kg^{-1}, while seed cost hovers around \$10 kg^{-1} depending on variety (Hancock Seed Co. n.d.). Teff also produces a high-quality forage with 2 to 3 cuts per season in Minnesota and is touted as an emergency forage that can be planted well into July and still produce biomass (Miller 2014; SDSU 2014; Twidwell et al. 2002). As a result, teff may be much more valuable in the upper Midwest as a forage crop than as a grain crop when planted after pennycress unless yields can be significantly increased.

2.4.6 Proso millet

In 2017 proso millet yielded nearly twice as high as millet in Minnesota variety trials (6,018 kg ha^{-1} vs 3,511 kg ha^{-1}) (Table 2.7; Tyl et al. 2018). Proso millet is particularly susceptible to seed loss from shatter if allowed to reach moisture levels suitable for storage while standing in the field, which is exacerbated with mechanical harvest (Henry et al. 2008; Baltensperger 1995). This is likely the main difference between the hand-harvested yields from our plots and the mechanically harvested variety trials. Herbicide damage in 2016 and gopher damage in 2018 make it difficult to discern if millet can consistently perform after pennycress. A study by Moomaw and Mader (1991) also had pest control issues planting proso millet as a double-crop after barley or wheat, demonstrating that appropriate in-season management is essential to success of a proso millet crop. University of Nebraska-Lincoln Extension recommends proso millet as an excellent double crop after winter wheat or sunflower, planting as late as early July

(Lyon et al. 2008). Nebraska has a longer growing season than Minnesota, but shorter season varieties of millet like those used in the field trials at Rosemount can make up for this difference. Proso millet can be found growing as far north as the 54° parallel, and HTT analysis shows that proso millet easily reaches harvestable maturity in the upper Midwest (Figure 2.1). Further research is needed to develop management practices to improve the reliability of proso millet yields, at which point proso millet will be a good choice as a summer annual to follow pennycress.

2.4.7 Buckwheat

Income from the pennycress-buckwheat system did not differ from the full-season soybean standard in 2017 or 2018 (Figure 2.2). Buckwheat grain was not obtained in 2016 due to lack of availability of appropriate threshing equipment. While yields were much lower than full-season soybean (Table 2.7), buckwheat price per weight was twice as high (NASS 2016, 2017, 2018). Average yield for buckwheat in North Dakota is 1,600 kg ha^{-1}, but average yield in the Rosemount field trial was 2,000 kg ha^{-1} (Table 2.7; Graves and Hall 2011). Because buckwheat exhibits indeterminate growth, larger operations generally cut and windrow buckwheat or wait for a frost to kill the plants before combining to avoid jamming harvest equipment with green stems (Bjorkman 2009). Harvesting by hand, as was done in the Rosemount trials, often reduces seed loss compared to combining, which may account for the higher than average yields. Previous studies have calculated losses of up to 30% attributed to mechanical harvest (Monti et al. 2009; Rodgers 2014).

In Missouri, buckwheat can be planted as late as early August (Myers 2002), while recommended planting in the Northeastern US ranges from mid-June through mid-July (Bjorkman 2009). In North Dakota, the largest producer of buckwheat grain in the US, recommended planting is from late-May through mid-June as a double-crop with early spring vegetables or winter grains or as a break crop between summer annual grains (Berglund 2007; Pavek 2016). Historical 30-year measurements of HTT indicate that buckwheat will reliably reach harvestable maturity at all four of the midwestern locations analyzed, making it an excellent choice for a double-crop after pennycress, especially if an early frost occurs (Figure 2.1).

2.4.8 Grain Sorghum

Grain sorghum was severely damaged by use of unsafened herbicide in 2016, and despite lack of herbicide injury in 2017 and 2018 did not reach harvestable maturity in either year. There is current research through South Dakota State University Extension to develop and evaluate shorter maturing varieties of grain sorghum for the upper Midwest and northern plains (Graham and Kleinjan 2019) but based on the 30-year analysis of HTT the average early-maturing variety of grain sorghum would not reliably reach harvestable maturity at any of the four sites included in this analysis (Kelley n.d.; Figure 2.1). However, there are multiple types of sorghum, and forage sorghum has low enough GDD requirements that it may fit well as a double-crop in the upper Midwest, as shown by Gesch and Archer (2013) who successfully planted forage sorghum after camelina, a winter annual crop related to pennycress.

2.4.9 Hemp

Income from industrial hemp was much lower than the soybean standard, and this analysis did not take into account additional costs such as growing permits and import costs for hemp seed, which totaled \$8.82 kg^{-1} compared to \$5.51 kg^{-1} for seed costs alone (Margaret Wiatrowski pers. comm. May 2019). This high investment cost currently outweighs potential gains, as conventional seed price at the elevator is only \$0.88 kg^{-1} (Figure 2.2). Seed producers claim that yields as low as 670 kg ha^{-1} for variety X-69 are enough to turn a profit, however yields in our study averaged 844 kg ha^{-1} and we calculated a net income of only \$37.56 ha^{-1} (Table 2.7; Figure 2.2) so it is unclear what factors seed producers used to make this conclusion (Legacy Hemp LLC 2019).

According to the 30-year HTT data, hemp requires too many GDD to maturity to be successfully double-cropped with pennycress at any of the locations in this study (Figure 2.1). However, hemp is photosensitive (Arnall et al. 2019), flowering when hours of darkness exceed 10 hours (Parr 2019). Plants in the Rosemount field study produced grain even though HTT were much lower than the reported 1955°C required to reach maturity (Figure 2.1; Table 1.1), suggesting that thermal units alone may not be the best predictor of hemp success.

Hemp in this study only reached 20% of its full height potential and had low yields (844 kg ha^{-1}) due to herbicide damage (personal observation). There are no broad-leaf herbicides registered for use in industrial hemp (CHTA 2019), but Buctril, the herbicide used in this study (Table 2.1) was chosen as the best possible alternative. Hemp variety 'X-59' averages yields between 900 and 1,680 kg ha^{-1}, and a hemp trial no-till planted after pennycress at the same date, rate, variety, and location yielded 29% more grain (1,035 kg ha^{-1}) than our trial, well within reported average yields, and had plants 3 to 4 times bigger in size than the hemp in our trial (Weiblen et al. 2018). Hemp requires a fine firm seedbed as it does not germinate well if soil is compacted (Parr 2019; Perdue University Hemp Project 2019; Anderson et al. 2019). This can be achieved through tillage and cultipacking or no-till seeding (CHTA 2019). Hemp no-till planted into pennycress stubble in the Weiblen (2018) trial yielded 18% less than hemp planted after pennycress plots had been tilled, indicating that seedbed has a large effect on grain yield, though this has not yet been quantified by other studies.

While hemp yields following pennycress were promising, this double-crop system is not yet economically lucrative (Figure 2.2). Additionally, results from Weiblen (2018) and issues with herbicide damage demonstrate further efforts to establish best management practices are needed before hemp can be widely recommended as a crop to follow pennycress.

2.4.10 Sweetcorn

Income from a pennycress-sweetcorn double-crop did not differ from a standard full-season soybean mono-crop in 2016 and 2017. However, late-planted sweetcorn comes with additional risks, as demonstrated by the negative income from the 2018 crop (Figure 2.2) that resulted from poor stand establishment. Corn earworm (*Helicoverpa zea*) infestations are also more prevalent in late-planted sweetcorn due to an increase in the number of egg-laying adults, which in turn decreases yield potential (Griffin and Williamson 2019; Williams 2008; Hallauer 2001). Ear and kernel quality were not assessed in this study, but based on visual observations 60 to 75% of ears in all years sustained corn earworm damage. In a study by Buntin et al. (2004) in the Southeastern US, 80% of ears in late-planted sweetcorn were infested with corn earworms. Based on

our predictions sweetcorn will reliably reach maturity across all locations, but earlier maturing varieties should be selected for both Morris and Prosper due to lower available HTT (Figure 2.1). If appropriate pest management strategies are utilized, sweetcorn is a profitable crop to follow pennycress.

2.4.11 Capstone Summary

The percentage of years that any given pennycress-summer annual double-cropping system will be a success varies depending on whether the past 30 or the past 10 years are considered (Table 2.6). Farmer recommendations should be made based on the most current climatic trends, and hence the 10-year probabilities should be used as a guide when choosing a summer annual to double-crop. At present, dry beans, proso millet, buckwheat, and sweetcorn can all be recommended as summer annuals to follow pennycress throughout the upper Midwest. However, the most conservative climate models predict a 0 to10% increase in GDD in Minnesota by 2040, and the most extreme models predict a 30 to 55% increase in GDD by 2100, with the most severe inflation occurring in the northern part of the state (Lant et al. 2016). As the climate warms and more GDD become available, the number of summer annual crops that can be successfully double-cropped will expand.

2.4.12 Future Work

This study focused on double-cropping grain crops with pennycress, but there are many possible systems that pennycress can be integrated into. Relay-cropping, whereby the second crop is planted into the still-maturing first crop, is another option. In this case the summer annual would be planted into a standing crop of pennycress (Berti et al. 2015, Johnson et al. 2017, Ott et al. 2019). Relay-cropping comes with its own challenges, e.g. timing planting and harvest to optimize yields of both crops and reduce competition between the winter annual and the interseeded crop. However, relay-cropping can increase the number of HTT that the summer annual has access to by getting it on the field earlier in the season. For locations with limited HTT, such as Prosper, relay-cropping may increase options for summer annuals that can reliably be grown in a multi-crop system. While grains and legumes are the most common crop types in the upper Midwest, short-season summer vegetables, such as sweetcorn, are also an option to

follow pennycress. These systems are often more specialized and have high-value products, which will impact economic feasibility.

The success of pennycress double-crop systems hinges on sufficient income from pennycress to offset the additional costs from management of two crops. The MN106 pennycress accession does not have stable yields due to issues with dormancy (Best and McIntyre 1975; Carlson 2018) and shatter (Dorn et al. 2015; Gesch et al. 2016). Reducing pennycress seed shatter and dormancy should be the focus of future agronomic and breeding work to eliminate them as major limiting factors to the profitability of pennycress double-cropping systems.

2.5 Conclusions

Pennycress is an ideal winter annual to double-crop in the upper Midwest due to its short life-cycle and winter hardiness, but it cannot be widely recommended until seed shatter can be reduced and yields stabilized. Dry bean and buckwheat can readily be cropped after pennycress, and while proso millet and sweetcorn will easily reach maturity after pennycress, effective pest management must be implemented to ensure marketable yields. Teff for grain will reach maturity when cropped after pennycress, but should only be grown as a forage due to its low seed value. Grain sorghum and full-season soybeans will not reach maturity in a double-crop system. Shorter season soybeans can reach harvestable maturity after pennycress, but cannot be recommended due to variable economic returns. Hemp can be potentially double-cropped after pennycress, but HTT cannot be used to reliably predict success. Before hemp can be recommended as a summer annual after pennycress, more research is needed to verify system agronomics.

The goal of this research was to assess potential summer annuals to incorporate into a double-crop rotation with pennycress based on economic profitability and environmental suitability in the upper Midwest. Taking into account economic performance and observed climate trends, dry beans, proso millet, buckwheat, and sweetcorn were the most promising summer annuals in this study to follow pennycress. Variable profitability of pennycress and the summer annuals across years indicates that further work is needed to optimize these systems in order to increase their appeal to farmers.

CHAPTER 3

EFFECTS OF SWEETCORN NITROGEN FERTILIZATION ON SUBSEQUENT PENNYCRESS YIELDS

3.1 Summary

Excess nutrient runoff from agricultural fields is the largest contributor to nutrient pollution of waterways worldwide. In the Midwestern US, corn dominates the landscape. As a crop, corn requires high amounts of nitrogen fertilizer to produce desirable yields while also exhibiting a relatively low nitrogen use efficiency, making corn cropping systems a target for improved nutrient management. Unlike field corn, sweetcorn has a short growing season while still requiring high nitrogen rates, presenting an opportunity for the incorporation of a winter annual cover crop to scavenge excess nitrogen. Pennycress is a winter annual Brassicaceae that has the potential to provide ecosystem services as well as an economic return through the harvest of its oil-rich seeds. We examined the effects of sweetcorn nitrogen fertilizer rates and pennycress planting method on pennycress yield. Cropping treatments included a no double-crop control and two methods of planting pennycress following sweetcorn harvest (broadcast and drill). Nitrogen rate and planting method had no effect on pennycress yield, biomass, or biomass nitrogen content, indicating that residual inorganic nitrogen after sweetcorn is sufficient to support a pennycress crop, and that broadcast seeding can be employed as the most cost-effective planting method. Residual inorganic soil nitrogen levels at pennycress planting increased with increasing rates of nitrogen applied to sweetcorn. Plots that had 200 kg N ha^{-1} applied to sweetcorn had residual soil N 38 to 80% greater than 0 N check plots. However, nitrogen treatment had no impact on residual soil N at pennycress harvest likely due to environmental losses. Treatments without pennycress had on average 27 to 42% greater residual inorganic soil nitrogen than plots with pennycress in three of the four site years. These results show that pennycress can act as a catch crop and reduce residual inorganic soil nitrogen, thus reducing nitrogen pollution of waterways from sweetcorn systems and potentially reducing fertilizer costs to farmers by keeping nitrogen in the field for a following crop.

3.2 Introduction

Sweetcorn (*Zea mays* convar. *Saccharate* var. *rugosa*) is a major crop in the upper Midwest, accounting for 37% of the total sweetcorn hectarage in the United States. Even so, sweetcorn makes up less than 1% of total cropland in the upper Midwest, while grain corn and soybean together account for 71% (USDA-NASS CDL 2018; NASS 2018). However, sweetcorn has a proportionally larger contribution to nitrogen pollution with three times the residual inorganic soil nitrogen of grain corn and soybean. This occurs as a result of the high fertilizer requirements to optimize ear or cut-kernel yield, which subsequently results in high-nitrogen residue left on the field after harvest (Rosen et al. 2017; Fritz et al. 2001; Andraski and Bundy 2005; 1999). Sweetcorn requires approximately 200 kg N ha^{-1} to achieve high-quality ears (Rosen et al. 2017; Bundy and Andraski 2005). While this fertilizer rate is comparable to recommendations for grain corn, sweetcorn is seeded at lower population densities and is harvested as a fresh vegetable rather than at grain maturity, meaning that as much as 34.3% to 50% of the nitrogen applied as fertilizer is not utilized by the crop and is susceptible to transport off-site (Kaiser et al. 2018; Prasad and Hochmuth 2016; Rosen et al. 2017).

Residual inorganic nitrogen has the potential to contaminate surface and groundwater, causing negative effects on both human and environmental health (MPCA 2014). In humid temperate climates such as the upper Midwest, the majority of nitrogen leaching occurs during the fall and spring due to rainfall and snowmelt during the shoulder season in summer annual cropping systems (Salmerón et al. 2010). Throughout much of the upper Midwest, the land is left bare during the shoulder season from November through May, exacerbating nitrogen loss. One way to mitigate the issue of N loss is through the use of winter annual cover crops.

Winter annual cover crops are cold hardy, and thus can be temporally positioned to uptake nitrogen in both the fall and the spring when the risk of leaching is highest (Teixeira et al. 2016; Heggenstaller et al. 2008). Compared to bare soil, winter annual cover crops can reduce nitrogen leaching by up to 80% (Staver and Brinsfield 1998), twice that of autumn cover crops (Thomsen and Hansen 2014). The dominance of winter-active genotypes in their ability to reduce nitrogen loss both within and across species has

been corroborated in a number of studies (Malcolm et al. 2014; 2015; McLenaghen et al. 1996; Teixeira et al. 2016; Valkama et al. 2015).

However, cover crops are only utilized on 2.3% of cropland in the Midwest (CTIC 2017). Research conducted in Iowa shows that producers stated more economic incentives and more diverse markets are necessary to increase cover crop adoption (Roesch-McNally et al. 2017). Other studies have similarly listed the need for better facilitating infrastructure such as technical assistance (Arbuckle and Roesch-McNally 2015) or cost-sharing (Singer et al. 2007) in order to increase the use of cover crops. The Chesapeake Bay area is one example where implementation of legislation that provides a monetary reward to farmers that cover crop has been a success. The Maryland Department of Agriculture's Cover Crop Program provides grants to farmers who plant cover crops, and from 2016 to 2017 over 226,210 ha of cover crops were planted in the state (Maryland Department of Agriculture 2017), which is equal to 43% of total commodity hectarage, the highest in the nation (USDA NASS 2019). Another alternative to legislative incentives is on-farm revenue increases (Reimer et al. 2012). Cash cover crops provide all the same environmental benefits as a cover crop but can also be harvested for profit, and may be a solution to the lack of cover crop adoption.

Pennycress (*Thlaspi arvense* L.) is a winter annual oilseed currently under development that may fit the need for a cash cover crop in the upper Midwest. Pennycress can provide a host of ecosystem services including early season pollinator foraging resources (Groeneveld and Klein 2014; Eberle et al. 2015), weed suppression (Johnson et al. 2015), erosion reduction (Gesch 2017), and reduction of nitrogen leaching. In double-cropped systems with soybean, pennycress significantly reduced nitrogen concentration in both the soil and leachate to a depth of 60 cm compared with a mono-cropped summer annual tilled system (Weyers et al. 2019, Thom et al. 2018; Johnson et al. 2017). Unlike many other cover crops, pennycress can provide farmers with direct economic returns through the harvest of its oil rich seeds, which contain 24-39% wt/wt oil (Sedbrook et al. 2014; Evangelista et al. 2012). High erucic acid and linoleic acid content (33 and 22 wt/wt%) makes the oil an excellent candidate for uses as a biofuel, industrial lubricant, and a component of biodegradable plastics (Sedbrook et al.

2014; Fan et al. 2013; Eberle et al. 2015; Sindelar and Schmer 2017; Cermak et al. 2013). Recent mutational breeding efforts have discovered pennycress strains with an oil profile comparable to canola, opening the market to products for human consumption (Chopra et al. 2019). Additionally, after seeds have been pressed for oil, the seedmeal can then be used as high-protein animal feed, fuel, and as a biofumigant depending on the oil and glucosinolate profiles (Johnson et al. 2015; Sindelar and Schmer 2017; Sedbrook et al. 2014; Fan et al. 2013).

Previous work on incorporating pennycress into cropping systems has focused on the effect of pennycress on the following crops, with little attention on the effect of the crops preceding pennycress (Johnson et al. 2015; Johnson et al. 2017; Phippen and Phippen 2012; Cubins 2019). Additionally, as a developing crop, agronomic best management practices such as adequate fertilizer regimens and planting methods have yet to be established (Cubins 2019). Only one study thus far has quantified the effects of fertilizer on pennycress yield and oil quality, and no significant difference was found between fertilizer rates (Rukavina et al. 2011). Similarly, only one study has examined the effect of drilling vs. broadcast planting pennycress seeds. Phippen et al. (2010a) found drilled plots outperformed broadcast planted plots regardless of seeding rate. However, a study by Carr (1993) postulated that broadcast planting would be preferable as pennycress is positively photoblastic (Hazebroek and Metzger 1990). The objectives of this study were to 1) determine the effect of planting method and sweetcorn nitrogen application on pennycress yield; and 2) analyze the effect of pennycress and nitrogen rate on residual inorganic soil nitrogen following sweetcorn.

3.3 Materials and Methods

3.3.1 Field Study

Studies were conducted at the Southern Research and Outreach Center (SROC) in Waseca, Minnesota and at the Rosemount Research and Outreach Center (RROC) in Rosemount, Minnesota from 2017 to 2019. The SROC plots (44°04’31”N 93°31’31”W) were located on a Webster/Nicollet clay loam soil, and the RROC plots (44°42’25”N 93°04’22”W) were located on a Waukegan silt loam. Precipitation and air temperature data (Table 3.2 and Table 3.3) were obtained from the NOAA reporting weather station at

SROC and RROC, respectively. Spring wheat was grown in the summer prior to all studies. The study was carried out as a randomized complete block design, with five nitrogen treatments: 0 (control), 65, 135, 135 as split applications of 67 (denoted as 135s), and 200 kg N ha^{-1} and three double-crop treatments: no pennycress (control), and two pennycress seeding methods (broadcast seeded and drill seeded) for a total of 15 treatments in four replications.

Sweetcorn variety "GSS 1477" was planted mid-June with a six-row planter (John Deere 7100 MaxEmerge, Deere and Co., Moline, IL) at a rate of 60,540 seeds ha^{-1} in 4.6 x 9 m plots at a depth of 3.8 cm with 76 cm row spacing. Fertilizer treatments were surface applied pre-plant as urea. The 135s treatment had 67 kg N ha^{-1} applied pre-plant, and the remaining 67 kg N ha^{-1} applied between the V4 and V6 growth stages. Sweetcorn was harvested by hand for fresh market yield at the end of August. Yields are not reported but were within averages for the surrounding county at each location. Corn stalks were cut and left in the field using a stalk chopper. Pennycress was planted directly into the corn stover using a no-till Brillion seeder (Landoll Corp., Marysville, KS) for the 'drill' treatments. An Avenger high-clearance tractor (LeeAgra Inc., Lubbock, TX) with an attached orbital air seeder (Gandy Co., Owatonna, MN) and disturbance units was used to establish 'broadcast' treatments in 15 cm rows at a depth of 0.3 cm. Pennycress was hand-harvested at maturity in mid-June and dried to constant weight in a 35°C oven before being threshed for grain yield using a stationary low profile plot thresher (Almaco, Nevada, IA) in 2016 and 2017, and a stationary Wintersteiger LD 350 thresher (Wintersteiger Inc., Salt Lake City, UT) in 2018.

Baseline soil samples (Table 3.1) were collected prior to sweetcorn planting on a site-wide basis from 0 to 60 cm depth, and analyzed for OM, W/V, CEC, pH, Ca, Mg, K, P, and total inorganic N (NH_4^+-N + NO_3^--N). Soil inorganic nitrogen at sweetcorn planting was 217, 65, 146, and 89 kg N ha^{-1} at Rosemount 2017, 2018 and Waseca 2017, 2018 respectively. Soil samples were also taken in each plot from 0-60 cm at pennycress planting and harvest and analyzed for inorganic nitrogen content. Aboveground biomass was hand harvested from a $0.5m^2$ quadrat in each plot when pennycress reached harvest maturity in mid-June, dried to constant weight at 95°C and ground before analysis with a

CN analyzer (vario Max cube, Elementar, Langenselbold Germany) to obtain percent nitrogen content. Percent nitrogen was multiplied by aboveground biomass weight to obtain N uptake.

3.3.2 Statistical Analysis

Statistical analyses were performed using the MIXED procedure in the statistical software SAS (SAS Institute Inc., Cary, NC). Year by location was a significant interaction for all parameters, so all parameters were analyzed by environment (site-year). Fixed effects were nitrogen treatment and double-crop treatment, and their interactions for residual inorganic soil nitrogen, pennycress yield, pennycress biomass, pennycress biomass nitrogen content. Random effects were block nested within year by location, and corresponding interactions with fixed effects. Individual analyses for residual inorganic soil nitrogen at two time points were conducted to enable comparison of fixed effects within a time point. To meet the requirement of common variance, residual inorganic soil nitrogen data was natural log transformed for analysis and backtransformed for presentation. Means for all response variables were separates using Fisher's LSD at P=0.05.

3.4 Results and Discussion

Residual inorganic soil nitrogen at pennycress planting was impacted by nitrogen treatment (Table 3.4), with higher residual inorganic nitrogen in plots that received higher rates of nitrogen fertilization on sweetcorn (Table 3.5). Residual inorganic soil nitrogen for all nitrogen treatments in three of four environments was higher in no-pennycress control plots than those with pennycress at the time of pennycress harvest (Figure 3.1, Table 3.6). Pennycress yields, aboveground biomass, and nitrogen uptake were not affected by nitrogen treatment or pennycress planting method in three of four environments (Table 3.4).

3.4.1 Soil Nitrogen

Nitrogen treatment affected residual inorganic soil nitrogen at pennycress planting across all environments (Table 3.4). Increasing rates of nitrogen applied to sweetcorn increased the level of residual inorganic soil nitrogen at pennycress planting (Table 3.5).

The 200 N treatment consistently had the highest residual inorganic soil nitrogen. The 0 and 65 N treatments consistently had the lowest residual inorganic soil nitrogen and were not different from each other. On average, the 200 N treatment had 38 to 80% more residual inorganic nitrogen than the 0 and 65 N treatments (Table 3.5). Similar results were found by Rosen et al. (2017) in a mono-cropped sweetcorn system, in which plots with 200 kg N ha^{-1} applied to sweetcorn averaged 40% higher residual N following harvest than plots where no nitrogen was applied.

Residual soil N in the 135 N and 135s N treatments were not different at pennycress planting in three of the four site years, the exception being Waseca 2018, in which the split application had higher residual N (Table 3.5). Additionally, in two of the four site years residual N in the 135s N treatment was not different from the 200 N treatment, while residual N in the 135 N treatment was always lower than the 200 N treatment. In studies on nitrogen fertilization timing on wheat (Alcoz et al. 1993) and maize (Jokela and Randall 1989, Ahmad et al. 2009), pre-plant nitrogen applications resulted in lower residual soil nitrate than split applications as plants at a later growth stage were unable to uptake all nitrogen applied due to less rapid growth. Conversely, Rosen et al. (2017) found no difference in residual inorganic soil nitrogen applied to sweetcorn as pre-plant or as a split application. However, more nitrogen taken up from the split application was allocated to ear production than in the pre-plant application, suggesting that yields and quality of sweetcorn may be improved with split applications of N fertilizer (Rosen et al. 2017).

Nitrogen treatment had no effect on residual inorganic nitrogen at pennycress harvest in three of four site years, likely due to environmental losses to leaching, runoff, and/or gas (volatilization or denitrification). At Rosemount in 2017 nitrogen treatment had an interactive effect with double-crop treatment on soil inorganic nitrogen at pennycress harvest (Figure 3.1). The no-pennycress check plots had higher residual N than plots with pennycress at all fertilizer rates except 0 kg N ha^{-1}. There was no difference in biomass or N uptake across N treatments at this field site (see section 3.4.3 to potentially explain this interaction.

Double-crop treatment had an effect on residual inorganic soil nitrogen at pennycress harvest in Rosemount 2018 and Waseca 2017. No-pennycress control plots had an average of 27 to 42% higher residual inorganic soil nitrogen than plots with pennycress across both environments, in which drilled and broadcast planting treatments did not differ (Table 3.6). Our findings were similar to previous research that pennycress is able to reduce residual inorganic soil nitrogen compared to bare ground in between summer annual crops (Weyers et al. 2019; Ott 2018; Johnson et al. 2017). At Waseca in 2018, untimely rains in the spring prevented herbicide treatment of fallow no-pennycress plots, resulting in heavy weed recruitment from the seedbank. While weeds are undesirable in an agricultural setting, they are a form of living cover and have been shown to reduce residual inorganic nitrogen in the soil (Premrov et al. 2014), which may account for the lack of difference in residual inorganic soil nitrogen between pennycress and fallow control plots at Waseca in 2018. Additionally, residual inorganic soil N did not differ between drilled and broadcast seeded pennycress plots in any site year (Table 3.2, Figure 3.1), showing that pennycress planting method did not affect the ability of pennycress to act as a nitrogen catch crop.

3.4.1 Pennycress Yields

Pennycress yield was not affected by nitrogen treatment in three of four site years (Table 3.4). Rukavina et al. (2011) found that pennycress seed production was maximized at 888 kg $ha^{-1}$with 56 kg N ha^{-1} applied to pennycress as a split application of 28 kg N ha^{-1} in the fall and spring. Residual inorganic soil nitrogen in the fall after sweetcorn harvest and before pennycress planting ranged from 28 to 172 kg N ha^{-1}, equal to or far exceeding the fall application in Rukavina's study. However, our yields were much lower than Rukavina et al. (Table 3.7) indicating that, while residual inorganic soil nitrogen following sweetcorn can support a pennycress crop, spring fertilization may be beneficial to yields.

Pennycress yield was not affected by planting method in any site year (Table 3.4). Drilling seed is more expensive and time-consuming (USDA NRCS 2005; Johnson 2000), so the ability to broadcast pennycress seed without affecting yield improves the economic feasibility of cropping systems including pennycress. However, this data

contradicts results by Phippen et al. (2010a) in which drilled plots consistently outperformed broadcast plots. Aiken et al. (2015) also found superior emergence and stand ratings for three oilseeds were achieved with a no-till drill compared to broadcast seeding. For most crops drilled planting is preferable to broadcast even with the increased implementation cost because increased seed-to-soil contact and uniform planting depth generally improve stand establishment (USDA NRCS 2005). However, pennycress may follow a different trend as a result of its positively photoblastic nature (Hazebroek and Metzger 1990), whereby seeds require a certain amount of light to germinate, and being planted any deeper than the surface could cause seeds to remain dormant. Future research should look closely at variables such as seed-soil contact, light availability, uniform planting depth, soil temperature, soil moisture, and soil type to elucidate the most effective planting method for pennycress (Phippen et al. 2010a, Carr 1993, Royo-Esnal et al. 2015; Gesch et al. 2016, Eberle et al. 2015).

Pennycress yields were low in all site years, which may have minimized treatment differences (Table 3.7). Pennycress variety ‘MN106’ has the potential to yield upwards of 2,000 kg ha^{-1} (Cubins 2019, Johnson et al. 2017), but in our trial yields ranged from 260 to 671 kg ha^{-1}. As a wild accession, MN106 still exhibits weedy characteristics. Seed shatter from preharvest dehiscing of silicles, is one of the more troublesome weedy traits (Sedbrook et al. 2014), as it can result in seed losses up to 300 times the initial seeding rate (Carlson 2018). Heavy rains in the week before pennycress harvest in all site years exacerbated seed lost to shatter and may be the primary reason seed yields were so low. In one study by Cubins (2019), pennycress seed lost to shatter accounted for up to 70% of the total yield. Breeders at the University of Minnesota are working to introgress genes that prevent shattering, which will reduce yield losses in future lines (Dorn et al. 2015).

3.4.3 Pennycress Biomass and Nitrogen Uptake

Pennycress planting treatment had no effect on aboveground pennycress biomass (Table 3.4), indicating that pennycress performed similarly regardless of how it was planted, again supporting the ability to choose the most economical planting method without altering pennycress performance (Noland 2017). Drilled plantings increase seed-to-soil contact compared to broadcast plantings, allowing for consistent and adequate

moisture transfer from the soil to the seed, which is essential for germination (USDA NRCS 2005; Royo-Esnal et al. 2015; Gesch et al. 2016; Johnson et al. 2017). However, previous research has shown that this benefit is greatest for larger-seeded crops, and benefit decreases with seed size (Hakansson et al. 2013). Reagan et al. (2018) also found that pennycress biomass did not differ between drilled and broadcast planting, corroborating the results of our study.

Pennycress biomass was not affected by nitrogen treatment across all environments (Table 3.4). Blackshaw et al. (2003), found a slightly different response, in which pennycress shoot biomass was higher in the 40 mg N kg^{-1} soil fertilizer treatment than the 0 mg N kg^{-1} soil treatment, but did not increase at fertilizer rates above 40 mg N kg^{-1}. However, Blackshaw's experiments were carried out in pots in a greenhouse environment, so it is possible that there are factors in the field that are limiting the ability of pennycress to produce biomass, such as nitrogen availability in the soil profile, timing of rain events or drought, and root structure. Additionally, the minimum fertilizer treatment in the Blackshaw experiment was 40 mg N kg^{-1} (approximately 90 kg N ha^{-1}) and increased up to 240 mg N kg^{-1} (approximately 540 kg N ha^{-1}) (soil depth: 0-15 cm, soil type: Typic Haplustoll sandy loam), much higher than the rates used in our study or that would be found under best management practices in the field. This may mean pennycress requires extremely concentrated levels of soil nitrogen in order to increase biomass.

Nitrogen uptake by pennycress was not affected by planting treatment, and was not affected by nitrogen treatment in three of four site years (Table 3.4). In Waseca 2017, the 200 N treatment had higher nitrogen uptake than all other nitrogen treatments (Table 3.7). Pennycress in our study sequestered 16 to 24 kg N ha^{-1} across all environments (Table 3.7). A study by Weyers et al. (2019) found that pennycress sequestered 35 to 40 kg N ha^{-1} by mid-spring compared with bare ground, much higher than our study. However, Weyers applied nitrogen fertilizer directly to pennycress in the spring, which may have increased the plant's nitrogen uptake. In addition, our plants were analyzed for nitrogen content at harvest maturity when carbon allocation is increased (Ranells and Wagger 1992) rather than mid-spring as in the Weyers study. In contrast, rye, the most

popular winter annual in the upper Midwest, sequesters two to 15 kg N ha^{-1} in the northern US (Wilson et al. 2019; Hively and Cox 2001), which follows results by Dean and Weil (2009) that show Brassicaceae sequester significantly more nitrogen than rye.

3.5 Conclusions

The rate of nitrogen applied to sweetcorn did not affect the following pennycress double-crop in terms of seed yield, total aboveground biomass, or biomass nitrogen content, indicating that maximum pennycress yields may be attained under relatively low fertilizer regimes. Higher fertilizer nitrogen applications to sweetcorn resulted in higher residual inorganic nitrogen at pennycress planting, but these differences did not carry through to the following summer regardless of the presence or absence of pennycress. Additionally, double-cropping pennycress after sweetcorn reduced residual inorganic soil nitrogen compared to following sweetcorn with fallow in three of four site years. While there may be a limit to the amount of nitrogen pennycress can sequester in the field, it still serves as an effective nitrogen catch crop. Planting method did not affect pennycress yields or residual inorganic soil nitrogen, promoting the use of broadcast planting as the least costly method of planting without jeopardizing pennycress yields. However, further research is needed to verify this finding across a range of environments, as drilled plantings of small-seeded crops historically outperform broadcast plantings.

Pennycress can be successfully grown utilizing only the residual inorganic nitrogen from a preceding sweetcorn crop. As a winter annual cash cover crop, pennycress has potential to follow sweetcorn. However, further research is needed to maximize pennycress yield and environmental benefits before this system can be recommended to farmers.

Table 1.1 Growth parameters for pennycress and potential summer annuals to double-crop after pennycress

Crop	Days to Maturity	GDD (°C)	water requirement (mm ha^{-1} yr^{-1})
Pennycress (*Thlaspi arvense*)	*	2190[§]	*
Soybean MG[ǂ] 1.4 (*Glycine max*)	97	1180	940-1570
Soybean MG 0.2 (*Glycine max*)	87	980	940-1570
Dry Bean (*Phaseolus vulgaris*)	80-105	840-930	360-460
Proso Millet (*Panicum miliaceum*)	60-90	865	330-360
Teff (*Eragrostis tef*)	90-130	*[1050]	430-510
Sorghum (*Sorghum bicolor*)	90-120	1470	450
Buckwheat (*Fagopyrum esculentum*)	70-90	700	*
Industrial Hemp (*Cannabis sativa*)	90-120	1955	250-300
Sweetcorn (*Zea mays* convar. *saccharata* var. *rugosa*)	60-100	800-950	1250-1880

[§] = Accumulated GDD for pennycress can be divided into fall – from planting until soil temperature equals 0°C (915-1022), winter – frozen soil until thaw (74-165), and spring – thaw until harvest (991-1204), though numbers vary widely by year.
[ǂ] = Maturity Group
* = no published data. Teff GDD based on field observations by Moore 2019. See Table 2.5 for average hydrothermal units for four Midwestern locations

Table 2.1 Crop management for field trials at Rosemount Research and Outreach Center, Rosemount, MN, 2015-2018

Year	Crop	Abbrev	Herbicide	Application Rate (kg ai ha^{-1})	Seeding Rate (kg ha^{-1})	Planting Date	Harvest Date
2015-2016	Pennycress 'MN106'	pc	none	N/A	11	9/3/2015	6/17/2016
	Sweetcorn 'GSS1477'	sweetcorn	Dual_II_Magnum	2.1	11	6/29/2016	10/6/2016
	Pinto Bean 'Stampede'	pinto	Dual_II_Magnum	2.1	90	6/29/2016	10/20/2016
	Kidney bean 'Montcalm'	kidney	Dual_II_Magnum	2.1	90	6/29/2016	10/20/2016
	Soybean .02 'MN0208CN'	soy02	Dual_II_Magnum	2.1	33	6/29/2016	10/20/2016
	Soybean .03 'FT-MN0306SP'	soy03	Dual_II_Magnum	2.1	75	6/29/2016	10/20/2016
	Soybean .07 'FT-M072074210'	soy07	Dual_II_Magnum	2.1	35	6/29/2016	10/20/2016
	Soybean .14 'MN1410R2F5121'	soy14	Dual_II_Magnum	2.1	42	6/29/2016	10/20/2016
	Proso millet 'Snobird'	pmSNO	Callisto	0.21	22	6/29/2016	10/20/2016
	Proso millet 'Sunrise'	pmSUN	Callisto	0.21	22	6/29/2016	10/20/2016
	Teff 'Tiffany'	teffTIFF	Dimetric	0.158	14	6/29/2016	10/20/2016
	Teff 'Summer Love'	teffSUM	Dimetric	0.158	14	6/29/2016	10/20/2016
	Buckwheat 'VNS'	buckwheat	none	none	50	6/29/2016	10/20/2016
	Grain Sorghum 'DGM71GB01'*	sorghum	Dual_II_Magnum	2.1	14	6/29/2016	10/20/2016
2016-2017	Pennycress 'MN106'	pc	none	N/A	11	9/20/2016	6/19/2017
	Sweetcorn 'GSS1477'	sweetcorn	Dual_II_Magnum	2.1	11	6/29/2017	9/28/2017
	Black bean 'Eclipse'	black	Dual_II_Magnum	2.1	90	6/29/2017	10/12/2017
	Cranberry bean 'ETNA'	cran	Dual_II_Magnum	2.1	90	6/29/2017	9/28/2017
	Pinto Bean 'Stampede'	pinto	Dual_II_Magnum	2.1	90	6/29/2017	10/25/2017
	Kidney bean 'Montcalm'	kidney	Dual_II_Magnum	2.1	90	6/29/2017	10/25/2017
	Soybean .02 'MN0208CN'	soy02	Dual_II_Magnum	2.1	33	6/29/2017	10/25/2017
	Soybean .03 'FT-MN0306SP'	soy03	Dual_II_Magnum	2.1	75	6/29/2017	10/25/2017
	Soybean .07 'FT-M072074210'	soy07	Dual_II_Magnum	2.1	35	6/29/2017	10/25/2017
	Soybean .14 'MN1410R2F5121'	soy14	Dual_II_Magnum	2.1	42	6/29/2017	10/25/2017

Table 2.1 (Cont.). Crop management for field trials at Rosemount Research and Outreach Center, Rosemount, MN, 2015-2018

Year	Crop	Abbrev	Pre-emergent Herbicide	Application Rate (kg ae ha^{-1})	Seeding Rate (kg ha^{-1})	Planting Date	Harvest Date
2016-2017	Proso millet 'Snobird'	pmSNO	Dual_II_Magnum	2.1	22	6/29/2017	9/29/2017
	Proso millet 'Sunrise'	pmSUN	Dual_II_Magnum	2.1	22	6/29/2017	9/29/2017
	Teff 'Tiffany'	teffTIFF	Dual_II_Magnum	2.1	14	6/29/2017	10/19/2017
	Teff 'Summer Love'	teffSUM	Dual_II_Magnum	2.1	14	6/29/2017	10/19/2017
	Buckwheat 'VNS'	buckwheat	Dual_II_Magnum	2.1	50	6/29/2017	9/28/2017
	Grain Sorghum 'DGM71GB01'*	sorghum	Dual_II_Magnum	2.1	14	6/29/2017	10/25/2017
2017-2018	Pennycress 'MN106'	pc	none	N/A	11	9/15/2017	6/22/2018
	Sweetcorn 'GSS1477'	sweetcorn	Laudis+MSO+AMS	0.09+1%v/v+9.5	11	7/2/2018	9/21/2018
	Black bean 'Eclipse'	black	Raptor+Basagran +NIS+AMS	0.018+0.42 +0.25%v/v+9.5	90	7/2/2018	10/5/2018
	Cranberry bean 'ETNA'	cran	Raptor+Basagran	0.018+0.42	90	7/2/2018	9/28/2018
	Pinto Bean 'Stampede'	pinto	Raptor+Basagran	0.018+0.42	90	7/2/2018	10/5/2018
	Kidney bean 'Montcalm'	kidney	Raptor+Basagran	0.018+0.42	90	7/2/2018	10/5/2018
	Soybean .02 'MN0208CN'	sou02	Raptor+Basagran	0.018+0.42	33	7/2/2018	10/12/2018
	Soybean .03 'FT-MN0306SP'	soy03	Raptor+Basagran	0.018+0.42	75	7/2/2018	10/19/2018
	Soybean .07 'FT-M072074210'	soy07	Raptor+Basagran	0.018+0.42	35	7/2/2018	10/19/2018
	Soybean .14 'MN1410R2F5121'	soy14	Raptor+Basagran	0.018+0.42	42	7/2/2018	10/19/2018
	Proso millet 'Snobird'	pmSNO	MPCA_2_Amine	0.623	22	7/2/2018	9/21/2018
	Proso millet 'Sunrise'	pmSUN	MPCA_2_Amine	0.623	22	7/2/2018	9/21/2018
	Teff 'Tiffany'	teffTIFF	MPCA_2_Amine	0.623	14	7/2/2018	9/28/2018
	Teff 'Summer Love'	teffSUM	MPCA_2_Amine	0.623	14	7/2/2018	9/28/2018
	Buckwheat 'VNS'	buckwheat	none	N/A	50	7/2/2018	9/21/2018
	Grain Sorghum 'DGM71GB01'*	sorghum	MPCA_2_Amine	0.623	14	7/2/2018	10/19/2018
	Hemp 'X-59'	hemp	Moxy 2E	0.68	56	7/2/2018	10/1/2018

* seeds treated with Concep

Table 2.2 Pre-plant soil characteristics of Rosemount, MN field sites by year at a depth of 0-60 cm.

Year	Soil Classification	OM%	*W/V*	CEC	pH	Ca	Mg	K	P	N
2016	Ostrander loam	4.2	1.55	--	6.6	--	--	96.1	11.6	
2017	Urban-land Waukegan complex	3.6	1.53	16.8	6.3	1713.8	428.5	73.3	8.3	
2018	Waukegan silt loam	3.8	1.53	20.5	6.6	1997.9	382.7	88.5	17.8	

OM% = percent organic matter, W/V=weight to volume (g cm^{-3}), CEC=cation exchange capacity (meq 100g), pH=active acidity (H^-), CA=calcium (ppm), Mg=magnesium (ppm), K=potassium (ppm), P=phosphorus (ppm), N=inorganic nitrogen (kg ha^{-1}).

Table 2.3 Monthly climate data and departure from norms for Rosemount, MN over the 2015-2018 study period.

	2015-2016				2016-2017			
	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal
Month	°C		mm		°C		mm	
Sep	18.7	2.7	126.0	33.8	18.1	2.1	132.8	40.6
Oct	10.3	1.4	66.7	-5.9	11.1	2.2	62.2	-10.4
Nov	4.5	4.4	110.1	56.7	6.2	6.1	45.2	-8.1
Dec	-1.6	6.6	65.2	34.2	-7.1	1.1	24.1	-6.9
Jan	-10.0	0.7	12.8	-13.6	-7.6	3.1	51.8	25.4
Feb	-5.3	2.5	13.5	-9.7	-1.9	5.8	16.0	-7.1
Mar	3.8	4.3	54.9	-3.6	-0.8	-0.3	16.0	-42.4
Apr	8.5	0.6	56.4	-17.7	9.0	1.1	115.6	41.4
May	15.5	1.3	69.9	-32.8	13.5	-0.8	182.4	79.8
Jun	21.0	1.4	81.3	-38.6	20.5	0.9	91.4	-28.5
Jul	24.8	2.9	120.7	6.4	22.3	0.4	138.7	24.4
Aug	21.4	0.6	178.3	58.2	18.9	-1.8	128.8	8.7
Sep	18.1	2.1	132.8	40.6	17.9	1.9	42.4	-49.8
Oct	11.1	2.2	62.2	-10.4	9.6	0.7	98.6	26.0

†Mean air temperature and accumulated precipitation were recorded from the NOAA reporting weather station at the Rosemount Research and Outreach Center, Rosemount, MN.

‡Calculated departure from the 1981-2010 30-year average temperature and accumulated precipitation using data collected at the Rosemount Research and Outreach Center (NOAA/NCEI, n.d.).

Table 2.3 (Cont.). Monthly climate data for the Rosemount, MN experimental site over the study period.

	2017-2018			
	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal
Month	---------------°C----------------		----------------mm----------------	
Sep	17.9	1.9	42.4	-49.8
Oct	9.6	0.7	98.6	26.0
Nov	-0.6	-0.7	1.8	-51.5
Dec	-8.2	0.0	8.4	-22.6
Jan	-11.1	-0.4	24.9	-1.5
Feb	-11.9	-4.2	28.2	5.1
Mar	-1.4	-0.9	23.1	-35.3
Apr	1.0	-6.9	50.3	-23.9
May	18.6	4.3	108.7	6.1
Jun	21.5	1.9	154.4	34.5
Jul	22.0	0.1	111.0	-3.3
Aug	21.1	0.4	102.1	-18.0
Sep	17.4	1.4	157.2	65.0
Oct	6.2	-2.7	90.9	18.3

Table 2.4 Studies reporting dry bean yields in the upper Midwest, conducted 1977-2015.

Study	Location	Year	Market Class	Yield (Mg ha^{-1})
Acosta-Gallegos and Adams 1991	MI	1987	F	2.65
Anderson et al. 2003	ND	1995-1997	A	1.44
Burnside et al. 1994	ND	1991-1992	I	1.85
	MN	1991-1993	E	2.77
	MN	1992	E	0.92
Burnside et al. 1998a	MN	1992-1993	G, E	1.73-2.27
Burnside et al. 1998b	MN	1993-1995	E	2.50
Deibert 1995	ND	1991-1993	G	0.87-2.39
Difonzo et al. 2015	MI	1993, 2008	G, A	1.33-3.39
Eckert et al. 2011a	ND	2008-2009	E, I	1.36-3.1
Eckert et al. 2011b	ND	2008-2009	I, A, G	2.12-2.37
Esteves de Jensen et al. 2002	MN	1997-1999	E	1.25-2.39
Goffnett et al. 2016	MI	2013-2014	A	2.66
Grafton et al. 1988	ND	1977, 1984-1985	G	2.71-3.95
Heilig and Kelly 2012	MI	2011-2013	A, G	1.52-2.57
Heilig et al. 2017	MI	2007-2009	J, H, A, I, G, C, E	1.40-3.85
Kelly et al. 1987	MI	1980-1985	--	2.38
Poling et al. 2009	MI	1998-1999	G, A	1.92-5.02
Soltani et al. 2016	ND	2014	B	2.68
Swegarden et al. 2016	MN	2013	I, A, G	2.12-2.37
Tautges et al. 2017	MN, Lamberton	2010-2015	A, E, G, I, D	0.89-1.65
	MN, Madison	2010-2015	A, E, G, I, D	1.26-2.56
	MN, Becker	2010-2015	A, E, G, I, D	2.05-2.85
	MN, Rosemount	2010-2015	A, E, G, I, D	1.95-3.08
Xu and Pierce 1998	MI	1989-1991	D	2.58-3.40

ǂ If more than one market class is indicated, yield was averaged across classes. A=black B=durango C=great northern D=heirloom E=kidney F=Mexican red G=navy H=pink I=pinto J=small red

-- study did not present data

Table 2.5 Average hydrothermal time available to summer annuals following pennycress at four Midwest locations over the past 30 and 10 year periods.

	Average HTT[ǂ] (°C)	
Location	30 -year	10-year
Ames	1288.983	1273.135
Morris	898.3402	948.73
Prosper	826.1921	895.7825
Rosemount	1151.949	1099.705

[ǂ] HTT calculated from pennycress harvest to first killing frost (-2°C) using a T_{base} of 10°C and a ψ_b of -1500 kPa.

Table 2.6 Percent success rate of summer annuals double-cropped after pennycress at four locations in the upper Midwest estimated using hydrothermal time.

		Estimated Success Rate by Summer Annual Species								
Location	Years*	dry bean	soy14	soy02	teff	pm	buckwheat	sorghum	hemp†	sweetcorn
		(%)								
Ames	30	100	86	97	97	100	100	7	0	100
	10	100	80	90	90	100	100	10	0	100
Rosemount	30	100	40	90	73	100	100	0	0	100
	10	100	20	70	60	100	100	0	0	100
Morris	30	73	0	27	10	67	90	0	0	77
	10	80	0	50	20	70	90	0	0	90
Prosper	30	39	0	14	4	36	86	0	0	64
	10	70	0	30	10	60	90	0	0	90

* Number of years in hindcast hydrothermal model

† Hemp is photosensitive, and growing degree days are likely not the best determinate of hemp success

See Table 2.5 for average hydrothermal units for all locations

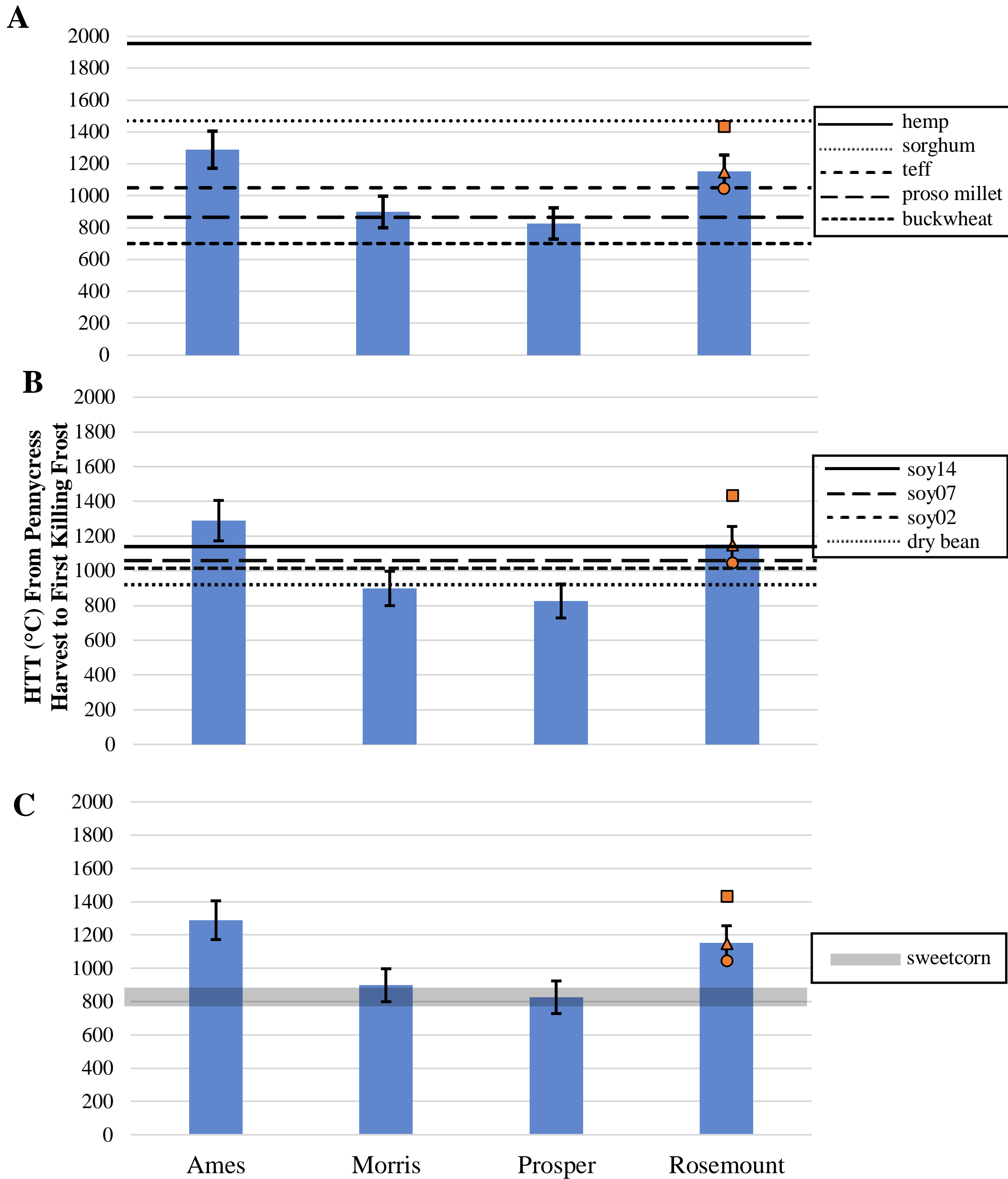

Figure 2.1 Historical hydrothermal time (HTT) 30-year mean for each summer annual following pennycress by location. Black bars indicate standard error. Horizonal lines indicate growing degree days (GDD) necessary to get the labeled crop to harvest maturity. Symbols for Rosemount indicate HTT for the years of the field study. ■ = 2016 ▲ = 2017 ● = 2018. Graphs are divided by crop type: small grains (A), legumes (B), and sweetcorn (C).

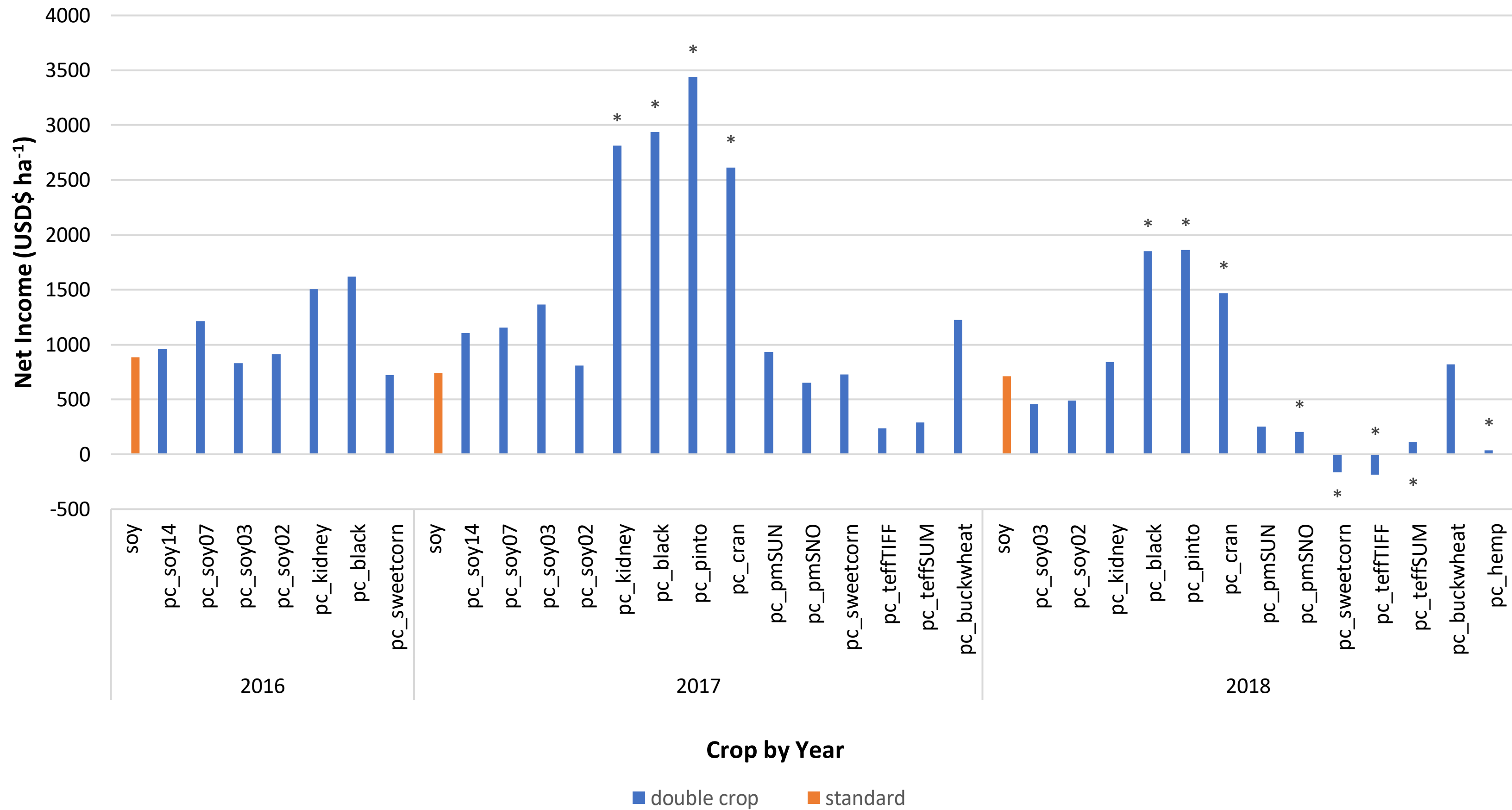

Figure 2.2 Net income of cropping system by year. Values marked with * differed within year ($p < 0.05$) compared to the standard in orange using a Dunnett's test. Standard is the county average for full-season mono-cropped soybean. See Table 2 for crop abbreviations.

Table 2.7 Average grain yield by year for summer annuals following pennycress, Rosemount, MN 2016-2018.

Summer Annual†	Yield (kg ha^{-1})		
	2016	2017	2018
soy14	3296	4136	--
soy07	3287	3473	--
soy03	2730	4536	2712
soy02	3095	3186	2941
kidney	2640	4740	2008
black	2809	4928	3430
pinto	--	5554	3336
cran	--	4453	2892
pmSUN	--	6840	3821
pmSNO	--	5196	3532
sweetcorn‡	14018	19566	6713
teffTIFF	--	1268	751
teffSUM	--	1374	1391
buckwheat	4409	2149	1837
sorghum	--	--	--
hemp	--	--	844
soy*	3921	3490	3591

† See Table 2 for crop abbreviations.
‡ Sweetcorn yields are reported as fresh weight
* Soybean yield for Dakota County (NASS 2016, 2017, 2018)

Table 3.1 Pre-plant soil characteristics of Rosemount and Waseca 2017 and 2018, MN field sites by year from 0-60 cm.

Site Year	Soil Classification	OM%	*W/V*	CEC	pH	Ca	Mg	K	P	N
Rosemount										
2017	Waukegan silt loam	4.7	1.53	26.5	5.9	2889.8	586.2	194.0	23.8	217
2018		3.6	1.53	16.7	6.1	1744.1	427.3	96.1	8.5	65
Waseca										
2017	Webster/Nicollet clay loam	3.9	1.45	24.0	6.2	2504.2	548.7	212.5	16.0	146
2018		5.3	1.44	36.9	6.3	4068.3	643.9	164.5	8.5	89

OM% = percent organic matter, W/V=weight to volume (g cm^{-3}), CEC=cation exchange capacity (meq 100g), pH=active acidity (H^{-}), CA=calcium (ppm), Mg=magnesium (ppm), K=potassium (ppm), P=phosphorus (ppm), N=inorganic nitrogen (kg ha^{-1}).

Table 3.2 Monthly climate data and departures from normal for Waseca, MN over the 2017-2018 and 2018-2019 growing seasons.

	2017-2018				2018-2019			
	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal
Month	---------------°C---------------		---------------mm---------------		---------------°C---------------		---------------mm---------------	
Jun	21.1	0.9	105.6	-14.0	21.5	1.2	146.9	27.3
Jul	23.1	0.9	166.7	54.0	21.7	-0.5	111.1	-1.6
Aug	19.1	-1.9	99.3	-21.8	20.7	-0.3	121.7	0.6
Sep	17.7	1.4	51.5	-42.1	17.8	1.5	267.7	174.1
Oct	9.8	0.8	105.1	37.0	6.4	-2.6	80.4	12.3
Nov	-0.4	-0.8	4.4	-50.7	-4.2	-4.6	34.2	-20.9
Dec	-8.4	-0.5	22.9	-14.8	-5.1	2.8	53.3	15.6
Jan	-11.7	-1.3	46.9	15.0	-11.2	-0.7	32.5	0.6
Feb	-11.7	-4.2	29.5	4.0	-14.1	-6.6	77.0	51.5
Mar	-1.6	-1.2	29.6	-33.9	-4.2	-3.7	51.0	-12.5
Apr	0.6	-7.2	89.4	7.5	6.9	-1.0	108.0	26.1
May	18.5	3.6	134.2	34.0	12.0	-2.8	161.1	60.9
Jun	21.5	1.2	146.9	27.3	20.2	0.0	84.7	-34.9

†Mean air temperature and accumulated precipitation were recorded from the NOAA reporting weather station at the Southern Research and Outreach Center, Waseca, MN.

‡Calculated departure from the 1981-2010 30-year average temperature and accumulated precipitation using data collected at the Southern Research and Outreach Center (NOAA/NCEI, n.d.).

Table 3.3 Monthly climate data and departures from normal for Rosemount, MN over the 2017-2018 and 2018-2019 growing seasons.

	2017-2018				2018-2019			
	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal	†Mean air temperature	‡Departure from normal	†Accumulated precipitation	‡Departure from normal
Month	---------------°C---------------		---------------mm---------------		---------------°C---------------		---------------mm---------------	
Jun	20.5	0.9	91.4	-28.5	21.5	1.9	154.4	34.5
Jul	22.3	0.4	138.7	24.4	22.0	0.1	111.0	-3.3
Aug	18.9	-1.8	128.8	8.7	21.1	0.4	102.1	-18.0
Sept	17.9	1.9	42.4	-49.8	17.4	1.4	157.2	65.0
Oct	9.6	0.7	98.6	26.0	6.2	-2.7	90.9	18.3
Nov	-0.6	-0.7	1.8	-51.5	-3.3	-3.4	37.6	-15.7
Dec	-8.2	0.0	8.4	-22.6	-5.0	3.2	47.2	16.3
Jan	-11.1	-0.4	24.9	-1.5	-11.0	-0.4	35.1	8.6
Feb	-11.9	-4.2	28.2	5.1	-13.2	-5.5	72.8	49.6
Mar	-1.4	-0.9	23.1	-35.3	-4.3	-3.8	59.2	0.8
Apr	1.0	-6.9	50.3	-23.9	6.5	-1.4	129.5	55.4
May	18.6	4.3	108.7	6.1	11.6	-2.6	173.0	70.3
Jun	21.5	1.9	154.4	34.5	20.0	0.4	119.8	-0.1

†Mean air temperature and accumulated precipitation were recorded from the NOAA reporting weather station at the Rosemount Research and Outreach Center, Rosemount, MN.

‡Calculated departure from the 1981-2010 30-year average temperature and accumulated precipitation using data collected at the Rosemount Research and Outreach Center (NOAA/NCEI, n.d.).

Table 3.4 Mixed-model analysis of variance of pennycress yield, residual inorganic soil nitrogen at pennycress planting and pennycress harvest, pennycress biomass, and pennycress nitrogen uptake.

		Residual Inorganic Soil N		Pennycress		
Environment	Fixed Effects	Planting	Harvest	Yield	Biomass	N Uptake
	Nitrogen	<0.001	<0.001	0.625	0.634	0.678
Rosemount 2017	Method	---	<0.001	0.834	0.574	0.396
	Nitrogen x Method	--	0.022	1	0.8366	0.844
	Nitrogen	<0.001	0.718	0.277	0.627	0.665
Rosemount 2018	Method	--	<0.001	0.073	0.49	0.299
	Nitrogen x Method	--	0.36	0.766	0.987	0.864
	Nitrogen	<0.001	0.116	<.001	0.057	0.047
Waseca 2017	Method	--	<0.001	0.572	0.105	0.097
	Nitrogen x Method	--	0.537	0.225	0.808	0.59
	Nitrogen	<0.001	0.197	0.265	0.909	0.78
Waseca 2018	Method	--	0.295	0.791	0.474	0.961
	Nitrogen x Method	--	0.211	0.43	0.706	0.611

Table 3.5 Residual inorganic soil nitrogen (kg ha^{-1}) by nitrogen treatment at pennycress planting at Rosemount and Waseca, MN in 2017 and 2018 from 0-60 cm.

	Rosemount				Waseca			
N Treatment	2017		2018		2017		2018	
0	28.0	C	33.8	C	33.8	C	52.9	C
65	33.8	C	47.9	C	42.1	BC	54.6	BC
135	61.1	B	85.1	B	45.6	B	62.4	B
135s	73.1	AB	77.3	B	42.4	BC	79.7	A
200	88.6	A	172.1	A	70.9	A	85.1	A

Letters within columns are significantly different $P<0.05$.

Data was log transformed for analysis and backtransformed for presentation

Table 3.6 Residual inorganic soil nitrogen (kg ha^{-1}) at pennycress harvest by pennycress planting treatment at Rosemount and Waseca, MN in 2017 and 2018 from 0-60 cm.

	Rosemount			Waseca			
Planting Treatment	2017*	2018		2017		2018	
none	--	55.1	A	78.4	A	41.0	A
broadcast	--	32.2	B	58.1	B	38.8	A
drilled	--	32.1	B	56.9	B	41.4	A

Letters within a column are significant at $P<0.05$

* There was a significant interaction between nitrogen treatment and planting treatment in Rosemount 2017. See Figure 3.1.

Data was log transformed for analysis and backtransformed for presentation.

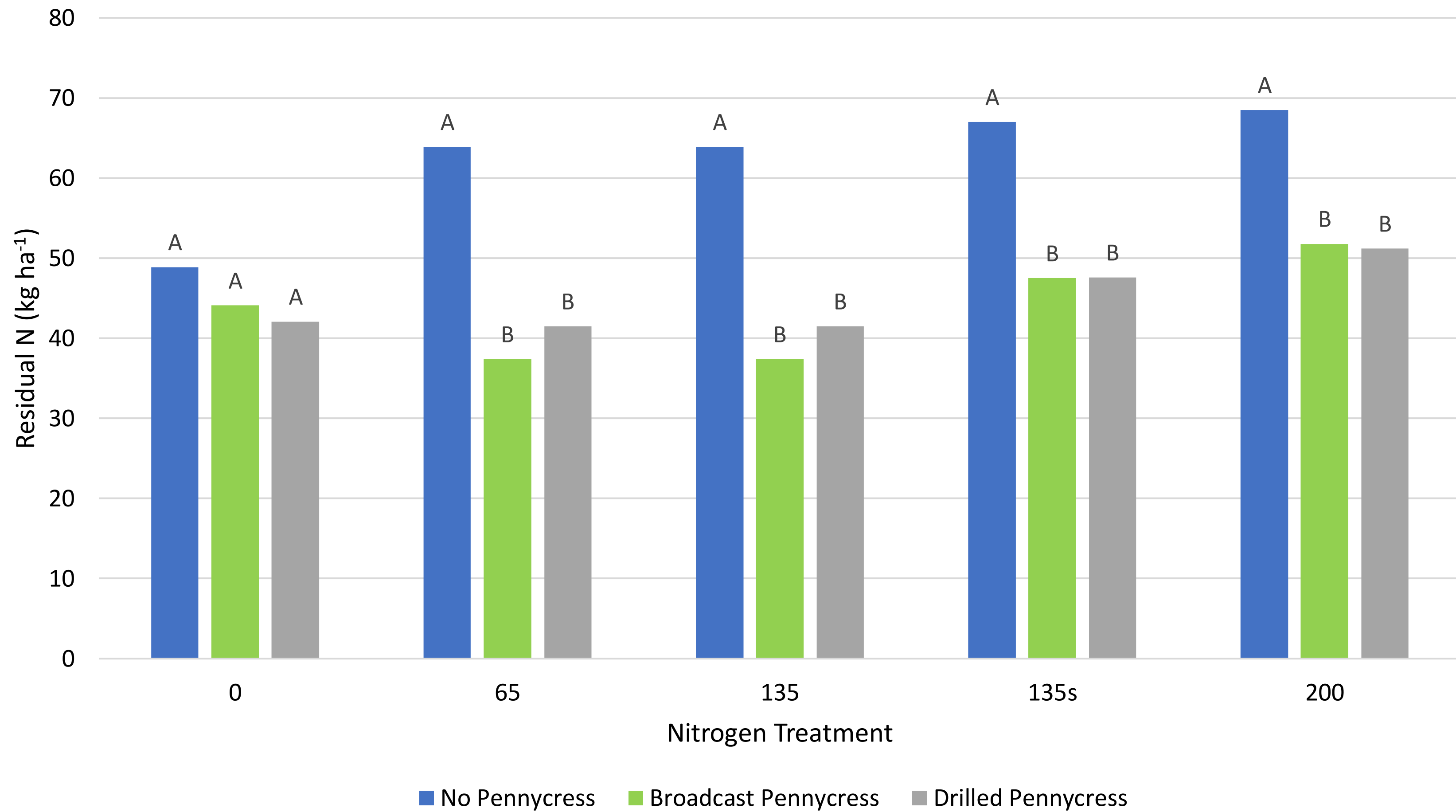

Figure 3.1 Interactive effect of sweetcorn nitrogen fertilizer rate (Nitrogen Treatment) and pennycress double-crop treatment on mean residual inorganic soil nitrogen at pennycress harvest for the Rosemount 2017 site year. Letters within nitrogen treatment are significant (P<0.05). Data was log transformed for analysis and backtransformed for presentation.

Table 3.7 Average biomass, nitrogen uptake, and seed yield for pennycress across all environments.

Environment*ǂ		Biomass	Nitrogen Uptake	Seed Yield
		---------------------------kg ha⁻¹---------------------------		
Rosemount 2017		1454.43	22.88	606.47
Rosemount 2018		1164.59	16.45	385.10
Waseca 2017		1019.28		
N treatment	0		17.74 B	329.43 BC
	65		17.16 B	260.01 D
	135		17.88 B	344.91 AB
	135s		17.52 B	266.54 CD
	200		21.47 A	396.91 A
Waseca 2018		1718.23	23.76	671.59

* Values are averaged across nitrogen treatment and planting method were not significant (*P*<0.05).

ǂ Letters within columns are significant (*P*<0.05).

REFERENCES

Acosta-Gallegos, J. A., & Adams, M. W. (1991). Plant traits and yield stability of dry bean (Phaseolus vulgaris) cultivars under drought stress. *J Ag Sci, 117*(2), 213-219. doi:10.1017/s0021859600065308

Agricultural Marketing Resource Center. (2018). Pennycress. Retrieved from https://www.agmrc.org/commodities-products/grains-oilseeds/pennycress

Aguilar, J., Gramig, G.G., Hendrickson, J.R., Archer, D.W., Forcella, F., Liebig, M.A. (2015). Crop species diversity changes in the United States: 1978 - 2012. *PLoS ONE.* 10(8). e0136580.

Ahmad, I., Iqbal, M., Ahmad, B., Ahmad, G., Shah, N.H. (2009). Maize yield, plant tissue and residual soil N as affected by nitrogen management and tillage systems. *J. Agric. Biol. Sci.* 1(1):19-29.

Aiken, R., Baltensperger, D., Krall, J., Pavlista, A., & Johnson, J. (2015). Planting methods affect emergence, flowering and yield of spring oilseed crops in the U.S. central High Plains. *Ind Crops & Prod. 69*, 273–277. doi: 10.1016/j.indcrop.2015.02.025

Alcoz, M.M., Hons, F.M., Haby, V.A. (1993). Nitrogen fertilization timing effect on wheat production, nitrogen uptake efficiency, and residual inorganic soil nitrogen. *Agron. J.* 85(6):1198- 1203. doi:10.2134/agronj1993.00021962008500060020x

Altieri, M.A. (1999). The ecological role of biodiversity in agroecosystems. *Ag. Ecosyst. Environ.* 74:19-31.

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A. (2015). Agroecology and the design of climate change- resilient farming systems. *Agron, Sustain. Dev*. 35:869-890.

Anderson, R. L., Tanaka, D. L., & Merrill, S. D. (2003). Yield and water use of broadleaf crops in a semiarid climate. *Ag Water Management, 58*(3), 255-266. doi:10.1016/s0378-3774(02)00085-9

Anderson, E., Baas, D., Burns, E., Chilvers, M., DeDecker, j., DiFonzo, C., Thelen, K., Thelen, M., Wilke, B. (2019). Industrial hemp production in Michigan. Michigan State University Extension Publication. E3402.

Andow, D. (1983). The extent of monoculture and its effects on insect pest populations with a particular reference to wheat and cotton. *Ag. Ecosyst. Environ*. 9: 25-35.

Andraski, T. W., and Bundy, L. G. (2005). Cover Crop Effects on Corn Yield Response to Nitrogen on an Irrigated Sandy Soil Research. *Agron. J.* 97:1239-1244. doi:10.2134/agronj2005.0052

Andraski, T.W., and Bundy, L.G. (1999). Nitrogen cycling in crop residues and cover crops on an irrigated sandy soil. *Agron. Abstr.* p. 244

Andrews, D. J. & Kassam, A. H. (1976). The importance of multiple cropping in increasing world food supplies. In M. Stelly (Ed.), Multiple cropping (pp. 1–10). Madison: American Society of Agronomy.

Arbuckle, J.G. and Roesch-McNally, G.E. (2015). Cover crop adoption in Iowa: The role of perceived practice characteristics. *J. Soil & Water Cons.* 70(6):418–429.

Arnall, B., Bushong, J., Lofton, J. (2019, May). Agronomic Considerations for Industrial Hemp Production. Oklahoma Cooperative Extension Fact Sheet. Retrieved from http://factsheets.okstate.edu/documents/pss-2921-agronomic-considerations-for-industrial-hemp-production/

Assefa, Y., Staggenborg, S.A., Prasad, V.P.V. (2010). Grain sorghum water requirement and responses to drought stress: A review. *CM.* doi:10.1094/CM-2010-1109- 01-RV.

Ballerstein, J. & Reiners, S. (2009). "N.Y.S. 2008 processing sweet corn variety replicated and observation (su and supersweet types) trial summary." in *Midwest vegetable trial report for 2009*. Retrieved from https://ag.purdue.edu/hla/fruitveg/MidWest%20Trial%20Reports/00_MVTR_ 2009_Web.pdf

Baltensperger, D., Lyon, D., Anderson, R., Holman, T., Stymiest, C., Shanahan, J., Nelson, L., DeBoer, K., Hein, G., Krall, J. (1995). Producing and marketing proso millet in the high plains. UNE Cooperative Extension EC 95-137-C.

Basche, A. D., Kaspar, T. C., Archontoulis, S. V., Jaynes, D. B., Sauer, T. J., Parkin, T. B., & Miguez, F. E. (2016). Soil water improvements with the long-term use of a winter rye cover crop. *Ag Water Management*, *172*, 40–50. doi: 10.1016/j.agwat.2016.04.006

Berglund, D.R. (2007a). Buckwheat production. NDSU Extension Publication A-687 (Revised).

Berglund, DR. (2007b). Proso millet in North Dakota. NDSU extension publication A-805

Berglund, D.R. (2011). Crops vary in their tolerance to frost. NDSU Extension Publication. Retrieved from https://www.ag.ndsu.edu/winterstorm/winter-storm-information-farm-and-ranch-information/farm-and-ranch-crops-general/crops-vary-in-their-tolerance-to-frost

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.

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

Best, K.F. and McIntyre, G.I. (1975). The biology of Canadian weeds. 9. Thlaspi arvense L. *Can. J. Plant Sci*. 55: 279–292.

Bishop, L. & Nelson, K.A. (2019). Field pennycress seeding date and corn herbicide management effects on corn, pennycress, and soybean production. *Agron. J.* 111:257–263. doi: 10.2134/agronj2018.03.0156

Bjorkman. (2009). Information for Buckwheat Growers. Cornell University College of Agriculture and Life Sciences New York State Agricultural Experiment Station. Retrieved from: http://www.hort.cornell.edu/bjorkman/lab/buck/guide/sowingwhen.php

Blackshaw, R. E., Brandt, R. N., Janzen, H. H., Entz, T., Grant, C. A., & Derksen, D. A. (2003). Differential response of weed species to added nitrogen. *Weed Sci, 51*(4), 532-539. doi:10.1614/0043-1745(2003)051[0532:drowst]2.0.co;2

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert G.W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agron. J.* 107:2449-2474.

Boland, M. (2016). Proso Millet. Retrieved from http://www.agmrc.org/commodities-products/grains-oilseeds/proso-millet/

Borchers, A. and Wallander, S. (2014, June 2). Double Cropping by U.S. Farmers Varies Over Time and Regionally. In *Deconstructing wheat price spikes: a model of supply and demand, financial speculation, and commodity price comovement.* (Janzen, J.P., Carter, C.A., Smith, A., Adjemian, M.K.). USDA Economic Research Service. April 2014. Retrieved from https://www.ers.usda.gov/amber-waves/2014/june/double-cropping-by-us-farmers-varies-over-time-and-regionally/

Borchers, A., Truex-Powell, E., Wallander, S., Nickerson, C. (2014). Multi-Cropping Practices: Recent Trends in Double Cropping. EIB-125. U.S. Dept of Agriculture, Economic Research Service.

Bósca, I. & Karus, M. (1998). The cultivation of hemp. HEMPTECH, Sebastopol, California, pp. 184.

Bundy, L. G., and Andraski, T. W. (2005). Recovery of Fertilizer Nitrogen in Crop Residues and Cover Crops on an Irrigated Sandy Soil. *Soil Sci. Soc. Am. J.* 69:640-648. doi:10.2136/sssaj2004.0216

Buntin, G.D., All, J.N., Lee, R.D., Wilson, D.M., (2004). Plant-incorporated *Bacillus thuringiensis* resistance for control of fall armyworm and corn earworm (Lepidoptera: Noctuidae) in corn. *J. Econ. Entomol.* 97(5): 1603-1611.

Burnside, O. C., Ahrens, W. H., Holder, B. J., Wiens, M. J., Johnson, M. M., & Ristau, E. A. (1994). Efficacy and Economics of Various Mechanical Plus Chemical Weed Control Systems in Dry Beans (Phaseolus vulgaris). *Weed Tech, 8*(2), 238-244. doi:10.1017/s0890037x00038719

Burnside, O. C., Wiens, M. J., Holder, B. J., Weisbere, S., Ristau, E. A., Johnson, M. M., & Cameron, J. H. (1998a). Critical periods for weed control in dry beans (Phaseolus vulgaris). *Weed Sci, 46*(3), 301-306. doi:10.1017/s0043174500089451

Burnside, O. C., Wiens, M. J., Krause, N. H., Weisberg, S., Ristau, E. A., Johnson, M. M., & Sheets, R. A. (1998b). Mechanical and Chemical Weed Control Systems for Kidney Bean (Phaseolus vulgaris). *Weed Tech, 12*(1), 174-178. doi:10.1017/s0890037x00042755

Byun, K. and Hamlet, A.F. (2018). Projected changes in future climate over the Midwest and Great Lakes region using downscaled CMIP5 ensemble. *Int. J. Climatol.* 38:531-553. DOI: 10.1002/joc.5388

Cal/West Seed. (2017, January 20). Growing Teff. Retrieved from http://teffgrass.com/

Carlson, R.J. (2018) Continuous living cover in a corn-soybean rotation: Management approaches and environmental benefits. Thesis, University of Minnesota.

Carr, P.M. (1993). Potential of fanweed and other weeds as novel industrial oilseed crops. In: Janick J, Simon JE (eds) New Crops. Wiley, New York, pp 384–388

Carter, P.R., Hicks, D.R., Oplinger, E.S., Doll, J.D., Bundy, L.G., Schuler, R.T., Holmes, B.J. (2019). Grain sorghum (milo). Alternative Field Crops Manual. UWI Extension and UMN Extension. Retrieved from https://hort.purdue.edu/newcrop/afcm/sorghum.html

Cermak, S.C., Biresaw, G., Isbell, T., Evangelista, R.L., Vaughn, S.F., Murray, R. (2013). New crop oils - properties as potential lubricants. *Ind. Crops & Prod*. 44: 232-239.

Channel. (2016). Irrigation Timing for Soybean. Agronomy Advice. Retrieved from http://www.channel.com/agronomics/Documents/AgronomicContentPDF/IrrigationTimingforSoybean.pdf

Chopra, R., Johnson, E.B., Emenecker, R., Cahoon, E.B., Lyons, J., Kliebenstein, D.J…. Marks, M.D. (2019). Progress toward the identification and stacking of crucial domestication traits in pennycress. Biorxiv. Retrieved from https://www.biorxiv.org/content/ 10.1101/609990v1.article-info

CHTA. (2019). Hemp production guide. Retrieved from http://www.hemptrade.ca/eguide

Clopton, J.R. & Triebold, H.O. (1944). Fanweed seed oil: Potential substitute for rapeseed oil. *Ind. & Eng. Chem.* 36(3):218–219. doi: 10.1021/ie50411a007

CREST. (2011). Climate Change and Renewable Energy: Management Foundations. MN DNR.

CTIC. (2017). Report of the 2016-17 National Cover Crop Survey. Joint publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association. West Lafayette, IN.

Cubins, J. (2019). Harvest time optimization of pennycress for use within the corn-soybean rotation. Thesis, University of Minnesota.

David, M.B., Flint, C.G., McIsaac, G.F., Gentry, L.E., Dolan, M.K., Czapar, G.F. (2013). Biophysical and social barriers restrict water quality improvements in the Mississippi River basin. *Environ. Sci. & Tech.* 47:11928–11929. doi:10.1021 /es403939n

Dean, J.E. and R.R.Weil. (2009). Brassica cover crops for nitrogen retention in the Mid-Atlantic Coastal Plain. *J. Environ. Qual*. 38:520–528. doi:10.2134/ jeq2008.0066

Deibert, E. J. (1995). Dry bean production with various tillage and residue management systems. *Soil & Tillage Research, 36*(3-4), 97-109. doi:10.1016/0167-1987(95)00506-4

Difonzo, C. D., Chludzinski, M. M., Jewett, M. R., & Springborn, F. (2015). Impact of Western Bean Cutworm (Lepidoptera: Noctuidae) Infestation and Insecticide Treatments on Damage and Marketable Yield of Michigan Dry Beans. *J Econ Entomol, 108*(2), 583-591. doi:10.1093/jee/tov037

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

Dorn, K.M., Fankhauser, J.D., Wyse, D.L., Marks, M.D. (2015). A draft genome of field pennycress (Thlaspi arvense) provides tools for the domestication of a new winter biofuel crop. *DNA Res*. 22(2): 121–131.

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

Eckert, F. R., Kandel, H. J., Johnson, B. L., Rojas-Cifuentes, G. A., Deplazes, C., Wal, A. J., & Osorno, J. M. (2011a). Row Spacing and Nitrogen Effects on Upright Pinto Bean Cultivars under Direct Harvest Conditions. *Agron J, 103*(5), 1314. doi:10.2134/agronj2010.0438

Eckert, F. R., Kandel, H. J., Johnson, B. L., Rojas-Cifuentes, G. A., Deplazes, C., Wal, A. J., & Osorno, J. M. (2011b). Seed Yield and Loss of Dry Bean Cultivars under Conventional and Direct Harvest. *Agron J, 103*(1), 129. doi:10.2134/agronj2010.0199

Egelkraut, T.M., Kissel, D.E., Cabrera, M.L. (2000). Effect of soil texture on nitrogen mineralized from cotton residues and compost. *J. Environ. Qual*. 29:1518-1522

Endres, G. & Kandel, H. (2016). Impact of planting dates on dry edible bean. NDSU Extension publication A1806.

EPA. (2019, April 15). Nutrient Pollution. The Effects: Human Health. Retrieved from https://www.epa.gov/nutrientpollution/effects-human-health

Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M. R., Leach, A.M., Vries, W. D. (2013). Consequences of human modification of the global nitrogen cycle. *Philosophical Transactions of the Royal Society B: Biological Sciences*. *368*(1621), 20130116. doi: 10.1098/rstb.2013.0116

Esteves de Jensen, C., Percich, J., & Graham, P. (2002). Integrated management strategies of bean root rot with Bacillus subtilis and Rhizobium in Minnesota. *Field Crops Research, 74*(2-3), 107-115. doi:10.1016/s0378-4290(01)00200-3

Evangelista, R. L., Cermak, S. C., Hojilla-Evangelista, M. P., Moser, B. R., & Isbell, T. A. (2017). Field Pennycress: A New Oilseed Crop for the Production of Biofuels, Lubricants, and High-Quality Proteins. *Surfactants in Tribology. 5:* 369-400. doi:10.1201/9781315120829-19

Evans, R., Lawley, Y., & Entz, M. (2016). Fall-seeded cereal cover crops differ in ability to facilitate low-till organic bean (Phaseolus vulgaris) production in a short-season growing environment. *Field Crops Research*, *191*, 91–100. doi: 10.1016/j.fcr.2016.02.020

Fan, J., Shonnard, D.R., Kalnes, T.N., Johnsen, P.B., Rao, S. (2013). A life cycle assessment of pennycress (*Thlaspi arvense* L.) - derived jet fuel and diesel. *Biomass & Bioenergy*. 55: 87-100.

Farris, A.L., Klonglan, E.D., Nomsen, R.M. (1977). The ring-necked pheasant in Iowa. Iowa conservation commission.

Fritz, V. A., Randall, G. W., Rosen C. J. (2001). Characterization and Utilization of Nitrogen Contained in Sweet Corn Silage Waste Contribution of the Minnesota Agric. Exp. Stn.. *Agron. J*. 93:627-633. doi:10.2134/agronj2001.933627x

Gabriel, J.L., Muñoz-Carpena, R., Quemada, M. (2012). The role of cover crops in irrigated systems: Water balance, nitrate leaching and soil mineral nitrogen accumulation. *Ag. Ecosyst. & Environ*. 155:50-61.

Galatowitsch, S., L. Frelich, and L. Phillips-Mao. (2009). Regional climate change adaptation strategies for biodiversity conservation in a midcontinental region of North America. *Biological Conservation*. 142:2012-2022.

Gerik, T., Bean, B., Vanderlip, R. (1998). Sorghum growth and development. Texas Cooperative Extension publication B-6137 7-03. Retrieved from http://glasscock.agrilife.org/files/2015/05/Sorghum-Growth-and-Development.pdf

Gesch, R.W. and Archer, D.W. (2013). Double-cropping with winter camelina in the northern corn belt to produce fuel and food. *Ind. Crops & Prod*. 44: 718-725.

Gesch, R.W., Archer, D.W., Berti, M.T. (2014). Dual cropping winter camelina with soybean in the Northern Corn Belt. *Agron. J*. 106 (5): 1735-1745.

Gesch, R.W., Isbell, T.A., Oblath, E.A., Allen, B.L., Archer, D.W., Brown, J., Hatfield, J.L., Jabro, J.D., Kiniry, J.R., Long, D.S., Vigil, M.F. (2015). Comparison of several Brassica species in the north central U.S. for potential jet fuel feedstock. *Ind. Crops & Prod*. 75: 2-7.

Gesch, R.W. and Johnson, J.M.F. (2015). Water use in camelina-soybean dual cropping systems. *Agron J.* 107(3):1098-1104.

Gesch, R.W. (2017). *Ecosystem Services Provided by Oilseed Cover Crops*. Power-point presentation.

Goffnett, A. M., Sprague, C. L., Mendoza, F., & Cichy, K. A. (2016). Preharvest Herbicide Treatments Affect Black Bean Desiccation, Yield, and Canned Bean Color. *Crop Sci, 56*(4), 1962. doi:10.2135/cropsci2015.08.0469

Government of Manitoba. (n.d.). Agriculture: Industrial hemp production and management. Retrieved from https://www.gov.mb.ca/agriculture/crops/production/print,hemp-production.html

Grafton, K.F. and Schneiter, A.A. (1985). Effect of planting dates on yield and other agronomic traits of dry bean. North Dakota farm research - North Dakota Agricultural Experiment Station. 42(6):11-13

Grafton, K. F., Schneiter, A. A., and Nagle, B. J. (1988). Row Spacing, Plant Population, and Genotype × Row Spacing Interaction Effects on Yield and Yield Components of Dry Bean. *Agron J, 80*(4), 631. doi:10.2134/agronj1988.00021962008000040017x

Graham, C. and Kleinjan, J. (2019, February 08). Sorghum Trial Results. SDSU Extension. Retrieved from https://extension.sdstate.edu/sorghum-trial-results

Grassini, P., Specht, J.E., Tollenaar, M., Ciampitti, I., Cassman, K.G. High-yield maize-soybean cropping systems in the US Corn Belt. In: Sadras VO, Calderini D, editors. Crop Physiology: Applications for Genetic Improvement and Agronomy. Amsterdam: Elsevier. 2014. pp. 17–41

Graves, I. and Hall, R. (2011). Buckwheat: A minor crop in South Dakota. South Dakota State University Extension publication. ExEx8006. Retrieved from https://openprairie.sdstate.edu/cgi/viewcontent.cgi?article=1237&context=extension_extra

Griffin, R.P., and Williamson, J. (2019). Insect Pests of Sweet Corn. Clemson Cooperative Extension Factsheet HGIC 2206. Retrieved from https://hgic.clemson.edu/factsheet/insect-pests-of-sweet-corn/

Groeneveld, J.H. & Klein, A. (2014). Pollination of two oil-producing plant species: Camelina (Camelina sativa L. Crantz) and pennycress (Thlaspi arvense L.) double-cropping in Germany. *GCB Bioenergy*. 6:242–251.

Groeneveld, J.H. & Klein, A. (2015). Pennycress-corn double-cropping increases ground beetle diversity. *Biomass & Bioenergy*. 77: 16-25.

Groeneveld, J.H., Lührs, H.P., Klein, A. (2015). Pennycress double-cropping does not negatively impact spider diversity. *Ag. & Forest Ent*. 17: 247-257.

Gubbels, G.H. (1978). Yield, seed weight, hull percentage, and testa colour of buckwheat at two soil moisture regimes. *Can. J. Plant Sci*. 58:881-883.

Habiyaremye, C., Matanguihan, J. B., Guedes, J. D. A., Ganjyal, G. M., Whiteman, M. R., Kidwell, K. K., Murphy, K. M. (2017). Proso Millet (Panicum miliaceum L.) and Its Potential for Cultivation in the Pacific Northwest, U.S.: A Review. *Frontiers in Plant Science*. 7, 1961. doi: 10.3389/fpls.2016.01961

Hakansson, I., J. Arvidsson, A. Etana, T. Rydberg, and T. Keller. (2013). Effects of seedbed properties on crop emergence: Temporal effects of temperature and sowing depth in seed-beds with favourable properties. *Acta Agric. Scand., Sect. B*. 61:458–468.

Hallauer, A.R. (ed). (2001). Specialty Corns Second Edition. CRC Press LLC. Boca Raton FL.

Hancock Seed Co. (n.d.). Tiffany Teff Grass Seed. Retrieved from https://hancockseed.com/collections/best-sellers/products/tiffany-teff-grass-seed?_pos=1&_sid=082178d1b&_ss=r

Hanrahan, B. R., Tank, J. L., Christopher, S. F., Mahl, U. H., Trentman, M. T., & Royer, T. V. (2018). Winter cover crops reduce nitrate loss in an agricultural watershed in the central U.S. *Ag. Ecosyst & Environ*, *265*, 513–523. doi: 10.1016/j.agee.2018.07.004

Hardman, L.L. & Gunsolus, J.L. (2002). Soybean Growth and Development and Management Information for Replant Decisions. Bulletin WW-05701. Univ. of Minnesota Extension.

Hartwig, N.L. & Ammon, H.U. (2002). Cover crops and living mulches. Weed Science 59th Anniversary - Invited Articles. 50:688-699.

Hazebroek, J.P. & Metzger, J.D. (1990). Environmental control of seed germination in Thlaspi arvense (Cruciferae). *Am J Bot.* 77:945–953. doi: 10.1002/j.1537-2197.1990.tb15189.x

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

Heilig, J. A., & Kelly, J. D. (2012). Performance of Dry Bean Genotypes Grown under Organic and Conventional Production Systems in Michigan. *Agron J, 104*(5), 1485. doi:10.2134/agronj2012.0082

Heilig, J. A., Wright, E. M., & Kelly, J. D. (2017). Symbiotic Nitrogen Fixation of Black and Navy Bean under Organic Production Systems. *Agron J, 109*(5), 2223. doi:10.2134/agronj2017.01.0051

Helm, J.L., Grafton, K.F., Schnelter, A.A. (1990). Dry bean production handbook. NDSU publication A-602.

Henry, W.B., Nielsen, D.C., Vigil, M.F., Cakderón, F.J., West, M.S. (2008). Proso millet yield and residue mass following direct harvest with a stripper-header. *J. Prod Ag.* 100(3):580-584. doi:10.2134/agronj2007.0268

Hively, W.D. and W.J. Cox. (2001). Interseeding cover crops into soybean and subsequent corn yields. *Agron. J.* 93:308–313. doi:10.2134/ agronj2001.932308x

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.

Holt-Giménez E. (2002). Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: A case study in participatory, sustainable land management impact monitoring. *Ag. Ecosyst. Environ.* 93: 87–105.

Igos, E., Vercisch, B., Koster, D., Benetto, E., Golkowska, K. (2016). Using rye as a cover crop for bioenergy production: an environmental and economic assessment, *Biomass & Bioenergy.* 95:116-123.

Ingrao, C., Lo Giusice, A., Bacenetti, J., Tricase, C., Dotelli, G., Fiala, M., Siracusa, V., Mbohwa, C. (2015). Energy and environmental assessment of industrial hemp for building applications: A review. *Renewable and Sus. Energy Reviews*. 51:29-42.

IPCC. (2018). Global warming of 1.5°C. *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Isbell, T.A. (2009). US effort in the development of new crops (Lesquerella, pennycress, coriander and cuphea). *OCL - Ol Corps Gras Lipides*. 16:205–210. doi: 10.1051/ocl.2009.0269

Jekanowski M. & Vocke G. Crop outlook reflects near-term prices and longer term market trends. USDA Amber Waves 20 May 2013. Retrieved from http://www.ers.usda.gov/amber-waves/2013-june/crop-outlook-reflects-near-term-prices-and-longer-term-market-trends.aspx#.VSf79pPveT8

Johnson, R.R. (1987). Crop management. In: Wilcox, J.R. (Ed.), Soybeans: Improvement, Production and Uses, 16, 2nd edition, pp. 355–390 (Agronomy).

Johnson, G.A., Kantar, M.B., Betts, K.J., Wyse, D.W. (2015). Field pennycress production and weed control in a double crop system with soybean in Minnesota. *Agron. J.* 107 (2):532-540.

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

Johnson, S.R. (2000 November). Estimated costs of pasture and hay production. Iowa State University Extension Publication. AG-96.

Jokela, W. E. and Randall, G. W. (1989). Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. *Agron. J. 81*(5): 720-726. doi:10.2134/agronj1989.00021962008100050004x

Kantar, M., Sheaffer, C., Porter, P., Krueger, E., Ochsner, T.E. (2011). Growth stage influences forage yield and quality of winter rye. *Forage & Grasslands*. 9(1). doi:10.1094/FG-2011-0126-01-RS.

Kazemi, H., Klug, H., Kamkar, B. (2018). New services and roles of biodiversity in modern agroecosystems: A review. *Ecological Indicators*. 93:1126-1135.

Kelley, J. (n.d.). *Grain Sorghum Production Handbook* (MP297-3M-1-04RV) (Cooperative Extension Service University of Arkansas) (L. Espinoza & J. Kelley, Eds.). Little Rock, AR: Cooperative Extension Service University of Arkansas. Retrieved from https://www.uaex.edu/publications/pdf/mp297/MP297.pdf.

Kelly, J. D., Adams, M. W., & Varner, G. V. (1987). Yield stability of determinate and indeterminate dry bean cultivars. *Theoretical & Applied Genetics, 74*(4), 516-521. doi:10.1007/bf00289831

Kelly, K.W. (2003). Double-cropping winter wheat and soybean improves net returns in the eastern Great Plains. *CM*. 2(1).

Klink, K., Wiersma, J. J., Crawford, C. J., & Stuthman, D. D. (2013). Impacts of temperature and precipitation variability in the Northern Plains of the United States and Canada on the productivity of spring barley and oat. *Int J Climatol.* 34(8): 2805–2818. doi: 10.1002/joc.3877

Kranz, W.L. & Specht, J.E. (2012). Irrigating soybean. NebGuide G1367. University of Nebraska-Lincoln Extension.

Kruidhof, H.M., Bastiaans, L., Kropff, M.J. (2008). Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. *Weed Research*. 48(6).

Krueger, E.S., Ochsner, T.E., Baker, J.M., Porter, P.M., Reicosky, D.C. (2012). Rye-Corn Silage Double-Cropping Reduces Corn Yield but Improves Environmental Impacts. *Agron. J.* 104 (4): 888-896.

Landis, D.A., Gardiner, M.M., van der Werf, W., Swinton, S.M. (2008). Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. PNAS 105:20552–20557. doi: 10.1073/pnas.0804951106

Lant, C., Stoebner, T. J., Schoof, J. T., & Crabb, B. (2016). The effect of climate change on rural land cover patterns in the Central United States. *Climatic Change*. *138*(3-4): 585–602. doi: 10.1007/s10584-016-1738-6

Legacy Hemp LLC. (2019). Certified X-59 Seed. Retrieved from https://legacyhemp.com/products

LeMahieu, P.J. & Brinkman, M.A. (1990). Double-cropping soybean after harvesting small grains as forage in the north central USA. *J of Production Ag*. 3: 385–389.

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

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B., Yang, H. (2010). A high-resolution assessment on global nitrogen flows in cropland. *PNAS*. 17: 8035-8040

Lucash, M. S., Scheller, R. M., Gustafson, E. J., & Sturtevant, B. R. (2017). Spatial resilience of forested landscapes under climate change and management. *Landscape Ecology*. *32*(5): 953–969. doi: 10.1007/s10980-017-0501-3

Lyon, D.J., Burgener, P.A., DeBoer, K.L., Harveson, R.M., Hein, G.L., Hergert, G.W., Holman, T.L., Johnson, J.J., Nleya, T., Krall, J.M., Nielsen, D.C., Vigil, M.F. (2008). Producing and marketing proso millet in the great plains. University of Nebraska Lincoln Extension. EC137. Retrieved from http://extensionpublications.unl.edu/assets/pdf/ec137.pdf

Malik, R.K., Green, T.H., Brown, G.F., Mays, D. (2000). Use of cover crops in short rotation hardwood plantations to control erosion. *Biomass & Bioenergy,* 18(6):479-487.

Mallinger, R.E., Franco, J.G., Prischmann-Voldseth, D.A, Prasifka, J.R. (2019). Annual cover crops for managed and wild bees: Optimal plant mixtures depend on pollinator enhancement goals. *Ag. Ecosyst. Environ*. 273:107-116.

Maloney, T.S., Oplinger, E.S., Albrecht, K.A. (1999). Small grains for fall and spring forage. *J. Prod. Ag*. 12:488–494.

Marra, M.C. & Carlson, G.A. (1986). Double-cropping wheat and soybeans in the southeast: input use and patterns of adoption. USDA Economic Research Service. Agricultural Economic Report 552.

Maryland Department of Agriculture. (2017). 2016-2017 Cover crop program acres planted summary by county. Retrieved from https://mda.maryland.gov/Documents/FY17 ccplant.pdf

Matthies, D. (1990). Plasticity of reproductive components at different stages of development in the annual plant *Thlaspi arvense* L. *Oceologia* 83:105–116. doi: 10.1007/BF00324641

Mays, D.A., Sistani, K.R., Malik, Ravi K. (2003). Use of winter annual cover crops to reduce soil nitrate levels. *J Sus Ag*. 21(4):5-19.

McCracken, D. (1989). Control of nitrate leaching with winter annual cover crops. UKT Department of Agronomy Soil Science News and Views. 10(2).

MDA (Minnesota Department of Agriculture). (n.d.). FAQs regarding Minnesota's industrial hemp pilot program. Retrieved from https://www.mda.state.mn.us/plants/hemp/ industhempquestions

Meisinger, J.J. & Ricigliano, K.A. (2017). Nitrate leaching from winter cereal cover crops using undisturbed soil-column lysimeters. *JEQ*. 46:576-584

Miller, D. (2014). Teff grass crop overview and forage production guide 2nd Ed. Cal/West Seeds. Retrieved from https://www.kingsagriseeds.com/wp-content/uploads/2014/12/Teff-Grass-Management-Guide.pdf

Mitich L. (1996) Field pennycress (*Thlaspi arvense* L.)-the stinkweed. *Weed Technol*. 10: 578–675.

Monti, A., Fazio, S., & Venturi, G. (2009). The discrepancy between plot and field yields: Harvest and storage losses of switchgrass. *Biomass & Bioenergy*. 33(5), 841–847. doi: 10.1016/j.biombioe.2009.01.006

Moomaw, R.S. and Mader, T.L. (1991). Double cropping seed and forage crops with small grains in the Upper Midwest. *J. Prod. Agric.* 4:385-390.

Mourtzinis, S., Gaska, J.M., Conley, S.P. (2016). UW Madison Extension. Cool Bean. Delineating optimal soybean maturity groups across the United States. Retrieved from http://www.coolbean.info/library/documents/SoybeanMG_2016_FINAL.pdf

MPCA. (2014). The Minnesota nutrient reduction strategy. Retrieved from https://www.pca.state.mn.us/sites/default/files/wq-s1-80.pdf

Myers, R.L. & Meinke, L.J. (1994). Buckwheat: a multi-purpose, short-season alternative. University of Missouri Extension Publication G4306. Retrieved from https://extension2.missouri.edu/G4306

Myers, R.L. (2002). Buckwheat: A versatile short-season crop. Thomas Jefferson Agricultural Institute Alternative Crop Guide. Retrieved from https://www.extension.iastate. edu/alternativeag/cropproduction/pdf/buckwheat_crop_guide.pdf

Naeve, S.L. & Nicolai, D. UMN Extension. (2018). Delayed Planting. Retrieved from https://extension.umn.edu/soybean-planting/delayed-planting#maturities-534811

NASS. (1997 December). Usual planting and harvesting dates of U.S. field crops. USDA Agricultural Handbook Number 628.

NASS. (n.d.). Quick Stats. Retrieved from https://www.nass.usda.gov/Quick_Stats/

NASS. (2012). Ag Census 2012. Retrieved from https://www.nass.usda.gov/Publications/ AgCensus/2012 /Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

NASS. (2017). Ag Overview: Minnesota. Retrieved from https://www.nass.usda.gov/ Quick_Stats/Ag_Overview/stateOverview.php?state=MINNESOTA

NCDC. (2016, 2017, 2018). Climate of Minnesota. Retrieved from https://web.archive.org/web/ 20060929052542/http://www5.ncdc.noaa.gov/climatenormals/clim60/states/Clim_MN_0 1.pdf

NDAWN. (n.d.). Soybean Growing Degree Days. Retrieved from https://ndawn.ndsu.nodak.edu/ soybean-growing-degree-days.html

Nleya, T., Walley, F. L., & Vandenberg, A. (2009). Response of Determinate and Indeterminate Common Bean Genotypes to Rhizobium Inoculant in a Short Season Rainfed Production System in the Canadian Prairie. *J Plant Nutr, 32*(1), 44-57. doi:10.1080/01904160802531001

NOAA/NCEI. (n.d.). Data Tools: 1981-2010 Normals. Retrieved from https://www.ncdc.noaa.gov/cdo-web/datatools/normals

Noland, R.L. (2017). Increasing sustainability of agricultural systems through adaptive crop management practices and technologies. Thesis, University of Minnesota.

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

Ostdiek, D. (2009). 8-21-09 Dry beans: Late planed beans likely to push the first frost. University of Nebraska-Lincoln Cropwatch.

Ott, M.A. (2018). *Four cover crops dual-cropped with soybean: Agronomics, income, and nutrient uptake across Minnesota*. Thesis. University of Minnesota.

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.

Parr, B. (2019, March). Industrial Hemp Grain Production. *Industrial Hemp Production Workshop*. Freeport, IL. Retrieved from https://www.youtube.com/watch?v= LJYvVIYo7b0

Pavek, P.L.S. (2016). Plant Guide for buckwheat (Fagopyrum esculentum). USDA-Natural Resources Conservation Service, Pullman Plant Materials Center. Pullman, WA.

Phippen, W., Gallant, J., Phippen, M. (2010a). *Evaluation of planting method and seeding rates with field pennycress (Thlaspi arvense L.)*. In: West. Illinois Univ. Retrieved from http://www.wiu.edu/pennycress/current-experiments/Plant Density 2010.pdf.

Phippen W, John B, Phippen M, Isbell T (2010b) Planting date, herbicide, and soybean rotation studies with field pennycress (Thlaspi arvense L.). In: West. Illinois Univ. http://www.wiu.edu/pennycress/current-experiments/Planting Date 2010.pdf.

Pippen, W.B. & Phippen, M.E. (2012). Soybean seed yield and quality as a response to field pennycress residue. *Crop Sci*. 52: 2767-2773.

Poling, K. W., Renner, K. A., & Penner, D. (2009). Dry Edible Bean Class and Cultivar Response to Dimethenamid and Metolachlor. *Weed Tech, 23*(1), 73-80. doi:10.1614/wt-07-092.1

Popović V., Sikora V., Glamočlija Dj., Ikanović J., Filipović V., Tabakovic M., Simić D. (2013). Influence of agro-ecological conditions and foliar fertilization on yield and yield components of buckwheat in conventional and organic cropping system. *Biotechnology in Animal Husbandry*. 29(3):537-546. doi:10.2298/bah1303537p

Prasad, R. & Hochmuth, G.J. (2016). Environmental nitrogen losses from commercial crop production systems in the Suwannee river basin of Florida (N.B Basu, ed.). *PLoS ONE*. 11(12): e0167558.

Premrov, A., Coxon, C.E., Hackett, R., Kirwan, L., Richards, K.G. (2014). Effects of over-winter green cover on soil solution nitrate concentrations beneath tillage land. *Sci Total Environ*. 470-471:967-974.

Purdue University Hemp Project. (2019). Hemp Production. Retrieved from https://dev.purduehemp.org/hemp-production/

Ramasubramaniam, H., Mendoza, L. E., & Bradley, C. A. (2008). Estimates of Yield and Economic Losses Associated with White Mold of Rain-Fed Dry Bean in North Dakota. *Agron J, 100*(2), 315. doi:10.2134/agrojnl2007.0127

Randall, G.W., Vetsch, J.A., Huffman, J.R. (2003). Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. *JEQ*. 32:1764–1772. doi:10.2134/jeq2003.1764

Randall, G.W. (2004). Subsurface Drain Flow Characteristics During a 15-Year Period in Minnesota. In Drainage VIII Proceedings of the Eighth International Symposium. 21-24 March 2004. Pp. 17-24. ASAE publication #701P0304, ed. R. Cooke.

Ranells, N.N. and Wagger, M.G. (1992). Nitrogen release from crimson clover in relation to plant growth stage and composition. *Agron J.* 84(3):424-430.

Reimer, A. P., Weinkauf, K., and Prokopy, L.S. (2012). The influence of perceptions of practice characteristics: An examination of agricultural best management practice adoption in two Indiana watersheds. *J. Rural Studies.* 28:118–128

Ren, L., Nest, T.V., Ruysschaert, G., D-Hose, T.K. Conelis, W.M. (2019), Short-term effects of cover crops and tillage methods on soil physical properties and maize growth in a sandy loam soil. *Soil & Tillage Research.* 192(192):76-86.

Robinson, R. G. (1980). The Buckwheat Crop in Minnesota. Station Bulletin 539. Agricultural Experiment Station, Univ. of Minnesota, St. Paul, MN.

Roesch-McNally, G., Basche, A., Arbuckle, J., Tyndall, J., Miguez, F., Bowman, T., & Clay, R. (2018). The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. *Renewable Ag & Food Syst*. 33(4):322-333.

Rodgers, A.D. (2014). Determining willingness to adopt mechanical harvesters among southeastern blueberry farmers. Thesis, Mississippi State Univ. Starkville

Roman, E.S., Murphy, S.D., Swanton, C.J. (2000). Simulation of Chenopodium album seedling emergence. *Weed Sci*. 48: 217–224.

Rosen, C., Crants, J., McNearney, M., Fritz, V., Rohwer, C. (2017). Establishing nitrogen credits following a sweet corn crop. MDA Grant Report.

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

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. doi: 10.1016/j.indcrop.2016.10.020

Rukavina, H., Sahm, D., Manthey, L., Phippen, W.B. (2011). *The Effect of Nitrogen Rate on Field Pennycress Yield and Oil Content*. In: West. Illinois Univ. Retrieved from http://www.wiu.edu/pennycress/current-experiments/Nitrogen 2011.pdf.

Russo, V.M. & Perkins-Veazie, P. 1992). Cultural practices affecting yield and nutrient content of drybean. *J. Prod. Agric*. 5(3):323-327

Salmerón, M., Cavero, J., Quíles, D., Isla, R. (2010). Winter cover crops affect monoculture maize yield and nitrogen leaching under irrigated Mediterranean conditions. *Agron. J.* 102:1700-1709.

Sands, G.R. (2018). Impact of agricultural drainage in Minnesota. University of Minnesota Extension. Retrieved from https://extension.umn.edu/agricultural-drainage/impact-agricultural-drainage-minnesota#drainage-in-the-upper-midwest-1360161

SARE. (2012). Managing Cover Crops Profitably, 3rd Edition. Retrieved from https://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/

Sauchyn, D., Kulshreshtha, S., and (and contributing authors). (2007). Prairies. In: From Impacts to Adaptation: Canada in a Changing Climate. pp. 275–328. Lemmen, D. S., Lacroix, J., and Bush, E., Eds. Government of Canada, Ottawa, ON.

Schläpfer, F. & Erickson, J.D. (2001). A biotic control perspective on nitrate contamination of groundwater from agricultural production. *Ag & Resource Econ Rev*. 30(2): 113-126.

SDSU. (2014, April). Consider Teff Grass for Emergency Forage, Hay Supplement. DakotaFarmer. Retrieved from https://www.farmprogress.com/story-consider-teff-grass-emergency-forage-hay-supplement-9-111286

Sedbrook, J., Phippen, W.B., Marks, D.M. (2014). New approaches to facilitate rapid domestication of a wild plant to an oilseed crop: Example pennycress. *Plant Sci*. 227:123-132.

Seeley, M.W. (2015). *Minnesota Weather Almanac: Second Edition, Completely Updated for the New Normals.* St. Paul, MN: Minnesota Historical Society Press. Project MUSE.

Seifert, C.A. & Lobell, D.A. (2015). Response of double cropping suitability to climate change in the United States. *Environ. Res. Lett.* 10: 024002

Sikora, V., Berenji, J., Latković, D. (2011). Influence of agroclimatic conditions on content of main cannabinoids in industrial hemp (Cannabis sativa L.). *Genetika.* 43. 10.2298/GENSR1103449S.

Selling, G.W., Hojilla-Evangelista, M.P., Evangelista, R.L., Isbell, T.A., Price, N., Doll, K.M. (2013). Extraction of proteins from pennycress seeds and press cake. *Ind. Crops & Prod*. 41:113-119.

Sindelar, A.J., Schmer, M.R., Gesch, R.W., Forcella, F., Eberle, C., 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.

Singer, J.W., Nusser, S.M., and Alf, C.J. (2007). Are cover crops being used in the US corn belt? *J. Soil & Water Cons*. 62(5):353–358.

Solomon, S., Qin, Q., Manning, M., Alley, R. B., Berntsen, T., Bindoff, N. L., …, Wratt, D. (2007). Technical summary. In: Climate Change: The Physical Science Basis. Cambridge University Press. Cambridge, UK.

Soltani, A., Bello, M., Mndolwa, E., Schroder, S., Moghaddam, S. M., Osorno, J. M., . . . Mcclean, P. E. (2016). Targeted Analysis of Dry Bean Growth Habit: Interrelationship among Architectural, Phenological, and Yield Components. *Crop Sci. 56*(6): 3005. doi:10.2135/cropsci2016.02.0119

Spalding, R.F. & Exner, E. (1993). Occurrence of nitrate in groundwater—a review. *JEQ*. 22(3):392-402.

Stallknecht, G.F. (1997). Teff. Perdue University New Crop Fact Sheet. Retrieved from https://hort.purdue.edu/newcrop/CropFactSheets/teff.html

Stallknecht, G.F., K.M. Gilbertson, J.L. Eckhoff. (1993). “Teff: Food crop for humans and animals.” p. 231-234. In: J. Janick and J.E. Simon (eds.), *New crops*. Wiley, New York.

Staver, K.W. & Brinsfield, R.B. (1998). Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. *J Soil and Water Cons*. 53:230-240.

Strock, J.S., Porter, P.M., Russelle, M.P. (2004). Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. Corn Belt. *JEQ*. 33:1010–1016. doi:10.2134/jeq2004.1010

Swegarden, H. R., Sheaffer, C. C., & Michaels, T. E. (2016). Yield Stability of Heirloom Dry Bean (Phaseolus vulgaris L.) Cultivars in Midwest Organic Production. *HortSci. 51*(1): 8-14. doi:10.21273/hortsci.51.1.8

Syswerda, S.P., Basso, B., Hamilton, S.K., Tausig, J.B., Robertson, G.P. (2012). Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. *Ag. Ecosyst. Environ*. 149:10-19.

Tautges, N., Flavin, C., Michaels, T., Ehlke, N., Lamb, J., Jungers, J., & Sheaffer, C. (2017). Rotating alfalfa with dry bean as an alternative to corn-soybean rotations in organic systems in the Upper Midwest. *Renewable Ag & Food Syst, 34*(1), 41-49. doi:10.1017/s1742170517000321

Thomsen, I.K. and Hansen, E.M. 2014. Cover crop growth and impact on N leaching as affected by pre- and postharvest sowing and time of incorporation. *S. Use & Mgmt.* 30:48-57.

Twidwell, E.K., A. Boe, and D.P. Casper. (2002). Teff: a new annual forage grass for South Dakota. ExEx 8071. Paper 278. Coop. Ext. Serv. South Dakota State Univ. Brookings, SD.

TX A&M Extension. (n.d.). Sweet Corn Crop Guide: Small Acreage Horticultural Crops. Retrieved from https://aggie-horticulture.tamu.edu/smallacreage/crops-guides/vegtables/sweet-corn/

Tyl, C. Marti, A., Hayek, J., Anderson, J., Ismail, B.P. (2018). Effect of growing location and variety on nutritional and functional properties of proso millet (*Panicum miliaceum*) grown as a double crop. *Cereal Chemistry.* 95(2): 288-301. doi:10.1002/cche.10028

USDA-ERS. (2019, August 20). Feedgrains sector at a glance. Retrieved from https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/feedgrains-sector-at-a-glance/

USDA-NASS. (2019). 2017 Census of Agriculture. United States summary and state data. Volume 1 Geographic Area Series Part 51. Publication AC-17-A-51.

USDA-NASS CDL (Cropland Data Layer). (2018). Published crop-specific data layer. USDA-NASS, Washington, DC. Retrieved from http://nassgeodata.gmu.edu/CropScape/ (accessed 28 April 2019).

USDA-NIFA. (2018). Industrial Hemp. Retrieved from https://nifa.usda.gov/industrial-hemp

USDC- NOAA/NCDC. (2013, March 01). *Summary of Annual Normals 1981-2010*. Retrieved from https://files.dnr.state.mn.us/natural_resources/climate/normals/freeze_dates/USC00217107.pdf

USDA-NRCS. (2005). Seedbed preparation and seed to soil contact. Technical Notes. Plant Materials – 6. Spokane, WA. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/wapmctn6330.pdf

USGS. (2018). Nitrogen and Water. Retrieved from https://www.usgs.gov/special-topic/water-science-school/science/nitrogen-and-water?qt-science_center_objects=0#qt-science_center_objects

USSEC (US Soybean Export Council). (2006). Chapter one: the soybean, it's history, and it's opportunities. *US Soy: International Buyers' Guide*. Retrieved from https://ussec.org/wp-content/uploads/2015/10/buyers-guide.pdf

UVM Extension Crops and Soils Team. (2011). Millet.

Vanburen, R., Wai, C. M., Pardo, J., Yocca, A. E., Wang, X., Wang, H., . . . Michael, T. P. (2019). Exceptional subgenome stability and functional divergence in allotetraploid teff, the primary cereal crop in Ethiopia. *BioRxiv*. doi:10.1101/580720

Van Meter, K.J., Basu, N.B., Veenstra, J.J., Burras, C.L. (2016). The nitrogen legacy: emerging evidence of nitrogen accumulation in anthropogenic landscapes. *Environ. Res. Lett*. 11 035014

Vaughn, S.F., Isbell, T.A., Weisleder, D., Berhow, M.A. (2005). Biofumigant compounds released by field pennycress (Thlaspi arvense) seedmeal. *J Chem Ecol*. 31:167–177. doi: 10.1007/s10886-005-0982-4

Vaughn, S.F., Palmquist, D.E., Duval, S.M., Berhow, M.A. (2006). Herbicidal activity of glucosinolate-containing seedmeals. *Weed Sci* 54:743–748. doi: 10.1614/WS-06-007R.1

Vrignon-Brenas, S., Celette, F., Piquet-Pissaloux, A., Corre-Hellou, G., David, C. (2018). Intercropping strategies of white clover with organic wheat to improve the trade-off between wheat yield, protein content and the provision of ecological serviced by white clover. *Field Crops Research*. 224:160-169.

Wang, Y., Chang, S. X., Fang, S., & Tian, Y. (2014). Contrasting decomposition rates and nutrient release patterns in mixed vs singular species litter in agroforestry systems. *Journal of Soils and Sediments*. *14*(6): 1071–1081. doi: 10.1007/s11368-014-0853-0

Weber, S. A. (2003). Archaeobotany at Harappa: Indications for change. In S. A. Weber & W. R. Belcher (Eds.), *Indus ethnobiology: New perspectives from the field* (pp. 175–198). Lanham: Lexington Books.

Weiblen, G., Wenger, J.P., Dabney, C III., Stutleberg, M. (2018 December). 2018 UMN-MDA Industrial hemp research project phase II summary report.

Weyers, S.L., Thom, M.D., Forcella, F., Eberle, C.A., Matthees, H., Gesch, R.W., Ott, M.A., Feyereisen, G.W., Strock, J.S., Wyse, D. (2019). Reduced potential for N loss in cover crop-soybean systems in a cold climate. *JEQ*. 48:660-669.

Williams II, M.M. (2008). Sweet corn growth and yield responses to planting dates of the north central U.S. *HortSci.* 43: 1775–1779.

Wilson, M.L., Allan, D.L., Baker, J.M., Pagliari, P.H. (2019). Comparing methods for overseeding winter rye into standing soybean. *Agroecosyst. Geosci. Environ.* 2:190023. doi:10.2134/age2019.04.0023

Wortman, S.E. (2016). Weedy fallow as an alternative strategy for reducing nitrogen loss from annual cropping systems. *Agron. Sustain. Dev*. 36:61

Xu, C., & Pierce, F. J. (1998). Dry Bean and Soil Response to Tillage and Row Spacing. *Agron J, 90*(3), 393. doi:10.2134/agronj1998.00021962009000030013x

Yost, M.A., Coulter, J.A., Russelle, M.P., Sheaffer, C.C., Kaiser, D.K. (2012). Alfalfa credit to first-year corn: potassium, regrowth, and tillage timing effects. *Agron J*. 104(4):953-962. doi: 10.2134/agronj2011.0384

Zhai, Y., Zhao, X., Teng, Y., Li, X., Zhang, J., Wu, J., & Zuo, R. (2017). Groundwater nitrate pollution and human health risk assessment by using HHRA model in an agricultural area, NE China. *Ecotoxicol Environ Saf*, *137*: 130–142. doi: 10.1016/j.ecoenv.2016.11.010