DEPARTMENT OF AGRICULTURE

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September 20, 2017

Chris Steller
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RE: PT contract #77355 MN Department of Agriculture (MDA) and University of Minnesota, Office of Sponsored Projects Final Report

Project: Dual Purpose Cover Crops and Onsite Retention of Water and Nutrients

Dear Chris:

Here is complete copy of the final report submitted to the Minnesota Department of Agriculture Pesticide and Management Division. The electronic copy was emailed to you on September 20, 2017.

I am submitting only one print copy. This report was prepared by the contractor and according to the project manager is not mandated by law.

Please contact me at (651) 201-6196 if you have questions.

Sincerely,

Kam Carlson

Kam Carlson
Contracts & Grants Coordinator
Pesticide & Fertilizer Management Division
Minnesota Department of Agriculture
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St. Paul, MN 55155-2538

Enclosures: One copy of final report for project listed above

Final Report

Dual-purpose cover crops and onsite retention of water and nutrients

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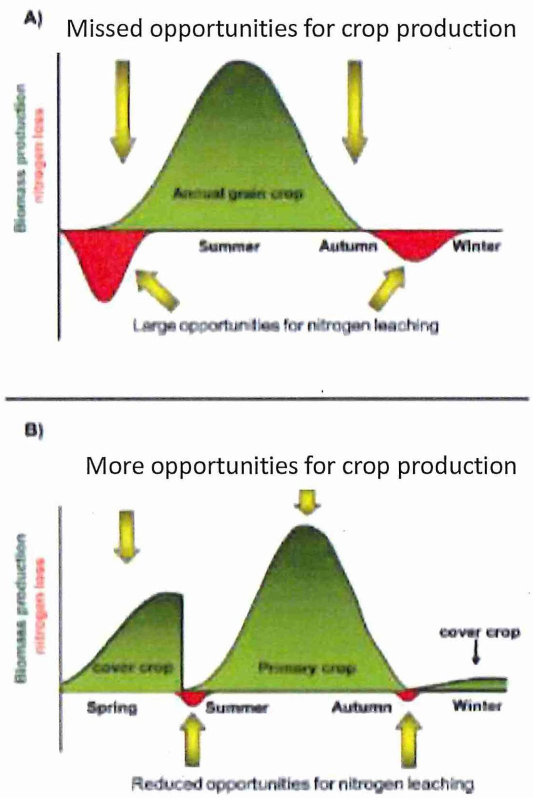
1. Relevance to MDA Impaired Waters Priorities

This proposal specifically targeted and was directly relevant to MDA Impaired Waters Research Priority #1: *Implementing cover crops into conventional cash grain cropping systems to capture nitrogen, reduce runoff and expand the window of crop water use.*

USDA-ARS and the University of Minnesota are partners in the Forever Green Initiative. A focus of this initiative was to develop cover-cropping systems that benefit Minnesota's agriculture and environment. Results from this research have assisted in developing an educational program on cover crops that is targeted toward agricultural professionals, growers, agency personnel, and environmental groups. This educational program included field days, grower meetings, ag-professional updates, and professional society meetings. The information transferred enables growers and agricultural professionals to make marked improvements in cover crop awareness and management, as well as water quality. The project was aimed specifically toward assessments of cover cropping techniques that have dual purposes: improving water quality while simultaneously maintaining or enhancing financial profitability of farms in Minnesota and elsewhere.

Two-thirds of Minnesota is farmland, and much of this land receives annual additions of nitrogen (N) and phosphorus (P) in the forms of fertilizer and manure. Offsite movements of these chemicals are the primary causes of impaired waters in our state. Retention of N and P in the fields on which they were applied is critically important to preserve and enhance water quality. A number of management and technical mechanisms exist for increasing N and P retention in arable fields, but many of these either are not implemented or are only partially successful. For instance, in the adjacent figure adapted from Heggenstaller et al. (2008), the presence of living cover crops like winter rye and triticale during autumn, winter, and spring is shown to greatly reduce opportunities for nitrogen leaching from typical Midwestern cropping systems dominated by corn. However, triticale, winter rye, and other such cover crops have been adopted by only 2% of our state's growers, primarily because they offer no obvious financial benefits. Consequently, new and alternative systems of retaining N and P in arable fields are needed – systems that clearly show economic advantages to Minnesota growers. Such new systems were the basis of this project.



Recently developed dual-purpose cropping systems in Minnesota were expected to reduce N and P losses markedly from arable fields. These systems also should lessen runoff and sediment flow substantially as well as use appreciably more soil water in autumn and early spring than traditional cropping systems. These new systems employ cash-generating winter cover crops (winter-hardy oilseeds) that are followed immediately by traditional cash grain crops. These oilseed crops are sown in late summer or early autumn immediately after harvest of wheat, soybean, corn silage, or early-harvested grain corn. They germinate immediately, form rosettes, and continue adding new growth until winter. By that time they have transpired soil water, scavenged mineral N in soil, and impeded water runoff and associated sediment-bound P. As growth of these hardy plants resumes promptly after snowmelt, in spring, so too do the water quality services they provide. For instance, winter camelina followed by soybean may use 60 mm (> 2") of soil water beyond that used by full-season soybean (Gesch and Johnson 2013).

The oilseed crops are harvested in late June and generate cash through their value for biodiesel and other oil-based products. The traditional cash grain crop, like soybean, enters the dual-cropping system the same year in either of two ways: relay-cropping or sequential cropping (described in the following paragraph). The combined cash generation potential of these crops is critical. Other winter cover crops, like winter rye or forage radish, also have environmental benefits, such as scavenging N (Strock et al. 2004, Dean and Weil 2009), widening the window of crop water use, hindering runoff, suppressing weeds (Forcella 2013, Forcella et al. 2014), and improving soil structure (Kadžienž et al., 2011; William and Weil, 2004). However, none of these cover crops generate cash for growers (unless they are grazed) and, accordingly, only a few growers make use of them. In contrast, yields of winter oilseeds can be substantial and financially lucrative, providing an incentive for growers to grow these crops.

Relay-cropping of the cash grain crop (e.g., soybean) is implemented at a near-traditional planting time by sowing soybean directly into the bolting oilseed crop. This typically occurs in late April or early May. Full-season soybean cultivars are used in relay-cropping. Early in the life of the young soybean the winter oilseed behaves like a nurse crop. The winter oilseed is harvested in late June, at which time it is about 60 cm (24") tall and the underlying soybean about only 20-30 cm (8-12") tall. This height differential allows for easy and effective combining of the winter oilseed with negligible damage to the soybean. This method has been investigated intensively by Gesch et al. (2013).

In contrast to relay-cropping is sequential cropping. Sequential cropping occurs when the cash grain crop is planted immediately (without tillage) following the harvest of the oilseed crop in late June. In this system the cash grain crop typically is a short-season soybean (maturity group at least one unit less than the local recommendation), dry edible bean, sunflower, or any other crop that tolerates abbreviated growing seasons. Although sequentially cropped soybean yields are less than maximal, net returns for the two crops combined (winter oilseed + soybean) usually are higher than that for traditional full-season soybean alone, but lower than that of the winter oilseed plus relayed soybean (Gesch and Archer 2013). Experiments in our project emphasized the higher yielding relay cropping system, but we also performed additional side-experiments (funded by other sources) on sequential cropping using a wide range of crops that can be grown in Minnesota. The most interesting of these crops, to date, are dry edible beans following winter camelina or pennycress.

2. **Project's Benefits to Minnesota Waters**

The results from this project already are being used by UMN extension personnel to promote new cropping systems that reduce N leaching into groundwater; lessen runoff, sediment and P entering surface waters; and shorten the timespans that water saturates surface soil layers in autumn and early spring. Widespread adoption of these new systems will lead to fewer algal blooms, and clearer, cleaner, and safer waters in Minnesota that will be more desirable for domestic, industrial, and recreational uses. Grower interest and likelihood of adoption of these new systems is increased because of their inherent financial advantages.

3. Objectives

Winter cover crops, like winter rye, are known to be effective at providing all of the ecosystem services mentioned above in fields previously fertilized heavily and cropped to corn (Snapp et al. 2005). Thus, our objectives were to compare new cover crops, which generate cash, with the more traditional cover crops (winter rye and forage radish) and conventional practice (winter fallow).

The new cropping system treatments that we tested are depicted in the idealized schematic of a single block of plots, as shown below, where **WC** is the winter oilseed, winter camelina; **PC** is another winter oilseed, pennycress; **Rye** is the traditional winter rye cover crop; **Radish** is the non-winter hardy cover crop often called forage radish or "tillage radish" in the popular press; and **Fallow** is the traditional winter fallow, which is maintained with a burndown herbicide in no-till and chisel-plowing in tilled systems. The Fallow systems represented the conventional "controls" for this experiment. Relay-planted soybean (**Relay Soy**) was compared to normally-sown soybean (**NS Soy**). The Relay Soy and NS Soy were the same cultivar with a full-season maturity group rating, but the former was planted into living vegetation (bolting winter oilseeds), whereas the latter was planted into bare soil or the residues of: a previous wheat crop, winter-killed radish, or glyphosate-treated winter rye.

WC	PC	Rye	Radish	Fallow	Fallow
Relay Soy	Relay Soy	NS Soy	NS Soy	NS Soy	NS Soy
No-till	No-till	No-till	No-till	No-till	Tilled

The null hypothesis that was tested is that a cropping system comprising winter camelina or pennycress, in comparison to standard full-season soybean, is equivalent in terms of (1) oil yields and total economic returns, (2) water use, (3) and fertilizer uptake and retention. The alternative hypothesis is that the camelina/soybean or pennycress/soybean system has higher oil yields, economic returns, water use, and N uptake and retention compared to a winter fallow followed by a standard full-season soybean crop.

Specific objectives were to compare agronomic, environmental, and economic consequences of these cropping systems. Agronomic items of interest included variables such as seed and oil yields. Environmental variables included N and P uptake, and concentrations of N and P in soil and soil water at differing depths. Measurements documented whether seasonal differences occurred among the cropping systems. Additionally, coarse measurements of runoff and sediment losses also were made across treatments. These latter measurements allowed levels of sediment-bound N and P to be estimated. Lastly, another objective was to extend the information resulting from this project widely across the state, region, and nation.

4. Deliverables

Results of this project are summarized in the form of four "deliverable," which are:

(1) A manuscript intended to be submitted to Agronomy Journal. This manuscript describes the three sites for the experiments, crop biomasses and yields, N and P sequestration, and coarse estimates of economic returns.

(2) A manuscript intended to be submitted to the Journal of Environmental Quality. This manuscript describes the results from the single, highly instrumented, research site that emphasized water quality research. Information in this manuscript details results from lysimeter and runoff studies, and it includes assessments of N and P in samples of leachate (lysimeters) and runoff (water and sediment).

(3) A draft version of the "Winter Camelina Growers' Guide" that can be used by farmers who may have an interest in trying winter camelina in a double-cropping system on their properties. A companion "Pennycress Growers' Guide" currently is in development.

(4) A list of technology transfer events that have involved project team members and in which results from this project have been featured.

Agronomy Journal manuscript

The following is merely a synopsis of the manuscript. Only highlights are presented. The actual manuscript can be found as an attachment to this report.

The three experimental location spanned the length and breadth of Minnesota (Figure 1). As expected, growing seasons were shorter and crop yields were less in Roseau than in Waseca. Nevertheless, all crops grew and produced harvestable yields in all locations. In fact, pennycress yields in Roseau were quite high compared to the two more southerly sites. Consequently, both winter oilseed cover crops (pennycress and winter camelina) clearly can tolerate winter conditions throughout Minnesota. More importantly, the values in Figure 2 also show that the double-cropping systems involving these winter oilseeds followed by soybean are workable systems throughout the state.

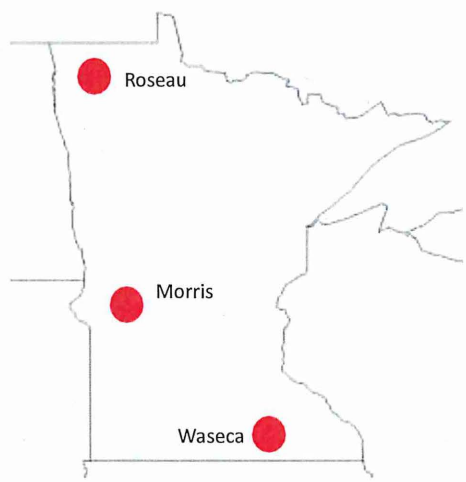


Figure 1. Experiments were performed at each of three locations over two growing seasons: 2014-2015, and 2016-2016.

Losses of N and P from agricultural fields can happen at any time of the year, but most losses occur in spring. Consequently, sequestration of N and P in spring has considerable value in terms of environmental quality. Our extensive data on N and P sequestration throughout the year are too cumbersome to show in this summary. Thus, only the values for the spring season are shown in Figure 3. Because radish winter-kills naturally, only the N results for winter rye, winter camelina, and pennycress are available. The values are remarkable. Because of the rapid growth of winter camelina and pennycress in spring, by May/June (maximum biomass of these crops), aboveground sequestration of N often surpassed 100 kg ha^{-1}, even in Roseau. Such sequestration of a labile utrient in living crop tissues means that it is unavailable for loss by leaching and/or runoff. For comparison, at that same time, N sequestration was zero in treatments with winter-killed radish or no cover crop (stubble and till).

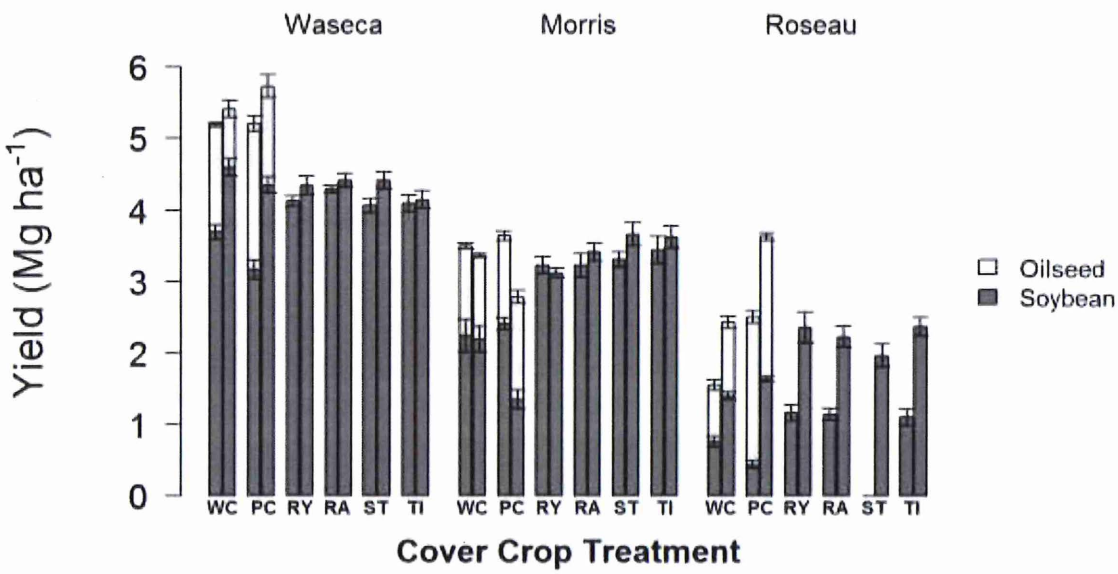


Figure 2. Yields of oilseeds and soybean during two growing seasons, 2014-2015 and 2015-2016, at three locations, and across six cover crop treatments: WC, winter camelina; PC, pennycress; RY, winter rye; RA, forage radish; ST, wheat stubble; and TI, conventional tillage.

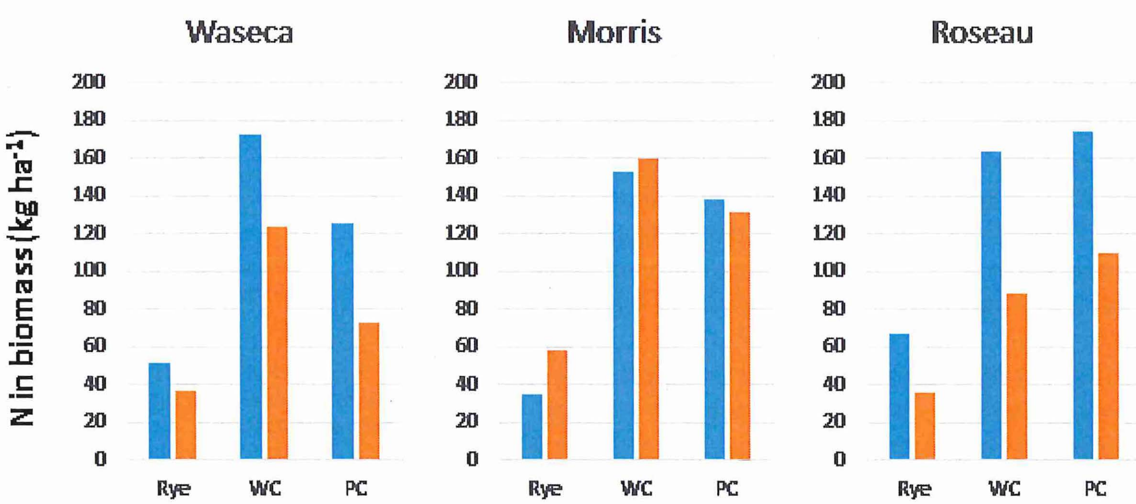


Figure 3. Springtime levels of N sequestered in biomass of three cover crops (Rye, winter rye; WC, winter camelina; and PC, pennycress) at three locations, and during two growing seasons (2014-2015, blue bars; and 2015-2016, brown bars).

Although the results shown in Figures 2 and 3 appear conclusive in terms of the ability winter camelina and pennycress to be grown in double-cropping systems in Minnesota and sequester large amounts of labile N in spring, additional information may be needed to convince growers to experiment with these crops on their farms. Information on the economic returns of these double-crops compared to mono-cropped soybean may be the type evidence needed. Accordingly, very coarse estimates of gross revenues were calculated for the six experimental treatments examined in Waseca, Morris, and Roseau (Table 1). As expected, gross returns were highest for Waseca, moderate for Morris, and lowest in Roseau, which perfectly matched the prevailing climates in those regions of Minnesota. More importantly, gross revenues in the double-crop systems never were less than those undergoing traditional management Till and Stubble management), and sometimes were significantly higher in both Waseca and Roseau. The gross returns for the cover crop treatments in Morris likely would have been higher if not for the distinct summer droughts during both growing seasons at this site.

Table 1. Comparison of combined soybean and oilseed gross revenue based upon plots containing various cover crop treatments.

	Waseca		Morris		Roseau	
	2015	2016	2015	2016	2015	2016
Cover Crop Treatment	----------------------	----------	$ha^{-1}	----------	----------	----------
None: Till	1662a	1682b	1398a	1470a	451b	964a
Stubble	1649a	1790ab	1342a	1485a	NA	799a
Radish	1742a	1793ab	1309a	1386a	466b	850a
Rye	1675a	1763ab	1310a	1266a	473b	960a
Camelina	2027a	2155ab	1353a	1302a	589b	935a
Pennycress	2007a	2251a	1413a	1057a	908a	1364a

2016 Calendar Year Mean Soybean Price: $406/Mg
2016 Calendar Year Mean Canola Price: $353/Mg
Values within columns followed by the same letter are not significantly different. Analyzed using Tukey's HSD.

Although the research summarized above shows consistent sequestration of labile soil nutrients by the winter cover crops, it does not demonstrate effects on water quality. Our research on nutrients in water is highlighted in the manuscript to be submitted to the Journal of Environmental Quality, a summary of which follows.

Journal of Environmental Quality manuscript

We assessed nutrient movement over two growing seasons in the six treatments outlined above at the Morris research site. Only a single site was monitored because of the intensity of measurements required for this type of research. During autumn, spring, and summer we monitored soil water in lysimeters and water and sediment in runoff troughs within 24 h after each precipitation event. Samples were not taken in winter due to frozen soil conditions. Moreover, water contamination by agricultural nutrients in Minnesota occurs primarily in spring (secondarily in autumn) through leaching and drainage (secondarily by runoff or overland flow). Accordingly, in the summary that follows the results from autumn and spring will be emphasized. The attached manuscript includes results from other time periods.

Nitrate concentrations of leachate in autumn and spring were affected greatly by cover crops (Figure 4). Radish and rye apparently sequestered so much N in autumn that little nitrate remained to be found in the soil solution. By spring, however, the winter-killed radish apparently released much N to the soil so that leachate in radish treatments contained high concentrations of nitrate. In contrast, springtime leachate under winter rye, winter camelina, and pennycress treatments had very little nitrate. These results correspond well with those from Figure 3 that show considerable N sequestration by camelina and pennycress crops in spring.

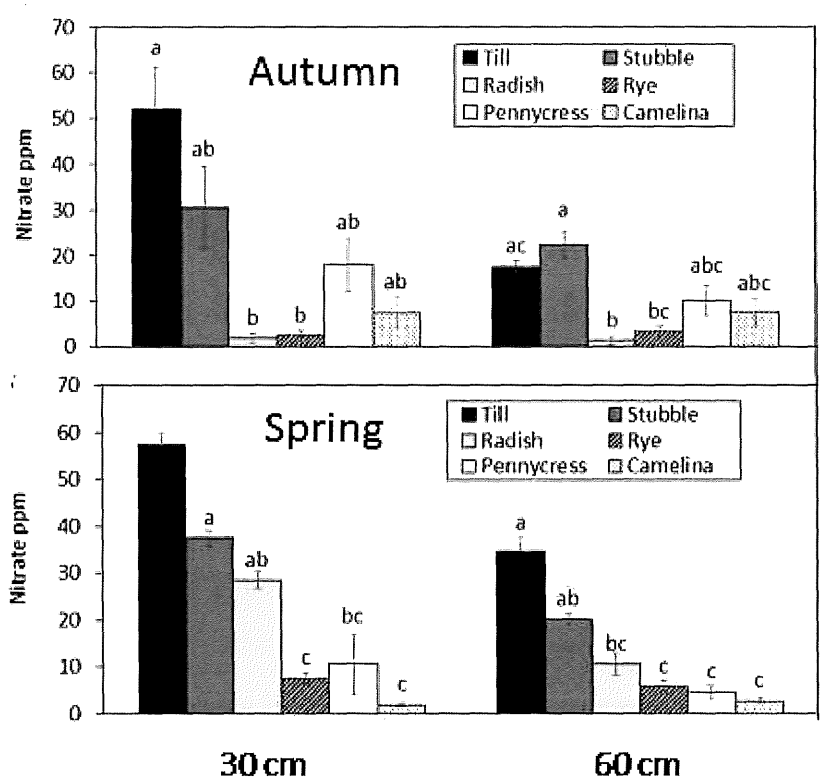


Figure 4. Nitrate concentrations in leachate during autumn (September-November) and spring (April-June) averaged over two growing seasons (2014-2015 and 2015-2016). Suction cup lysimeters were placed at 30 and 60 cm soil depths in September of each year and remained in place until September the flowing year. Experimental site was the Swan lake Research Farm, near Morris, Stevens County, Minnesota.

Runoff results are depicted in Figure 5 for three time periods: autumn, spring, and summer. Results are averaged over the two growing seasons (2014-2015 and 2015-2016). Few differences were observed among treatments, although variability did exist among seasons, with lowest values for N occurring in spring. From these runoff results, no definitive conclusions can be drawn regarding off-site movements of either N or P.

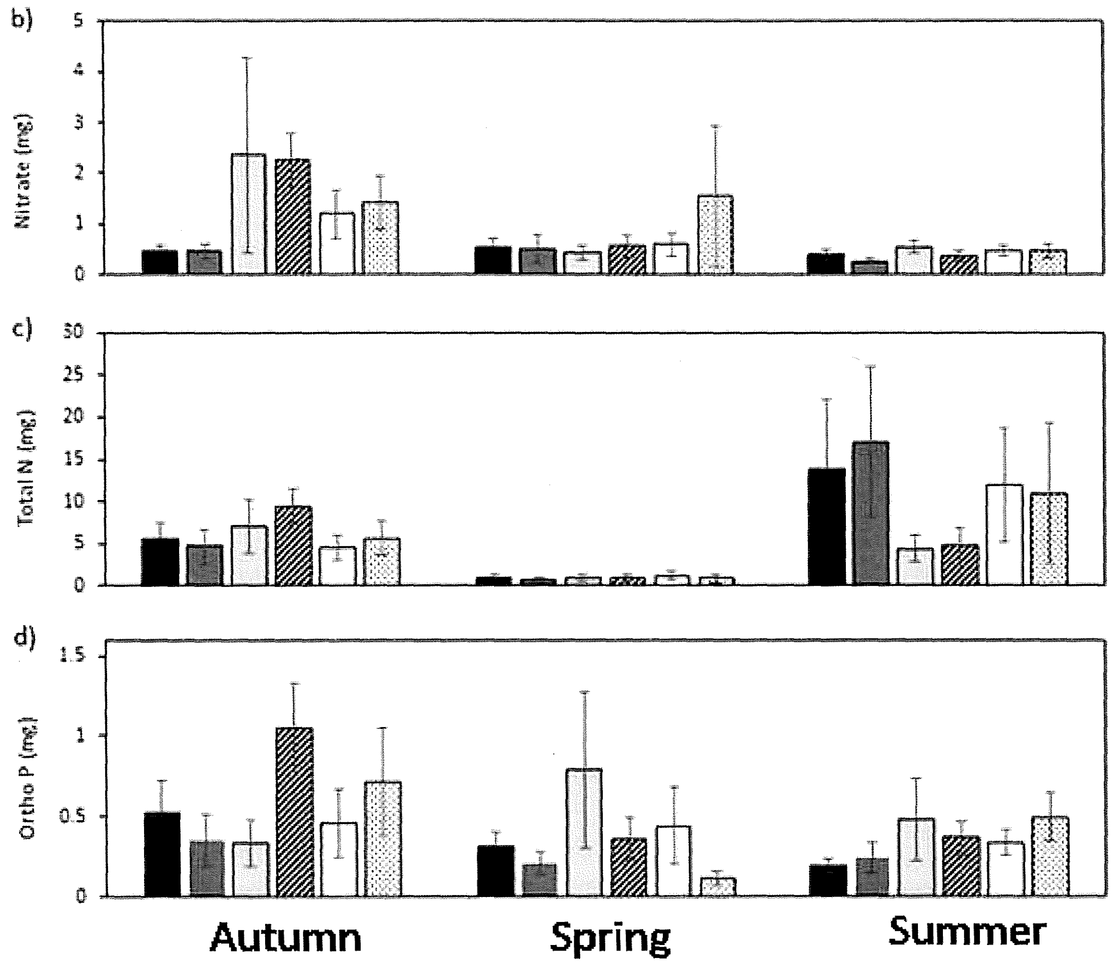


Figure 4. Amounts of N and P collected from runoff troughs installed in experimental plots at the Swan Lake Research Farm, Morris, MN, during three seasons. Columns are pooled means (±SE).

Camelina Growers' Guide draft document

The guide is attached to this report, but to avoid redundancy, it is not embedded in it. The guide provides the following sections to its readers:

1 Overview of winter camelina and the double-crop system

2 Variety selection

3 Field selection

4 Planting time and seedbed preparation

5 Seeding depth

6 Seeding rate and row spacing

7 Weed control

8 Fertility

9 Drilling soybean and other crops into camelina

10 Combine harvesting

11 Seed storage

12 Ecosystem services

As mentioned previously, a similar growers' guide is under development for pennycress.

6. Education and outreach

1. Ott M, Gescg RW, Wyse DL, and Forcella F. 2015. Improving Minnesota's Water Quality with Cash Cover Crops. ASA paper.
2. Johnson GA, Wells MS, Anderson K, Gesch RW, Forcella F and Wyse DL. 2016.,Field Pennycress and Camelina Oilseed Yield in a Relay Cropping System with Soybean. ASA Poster Number 452-1004
3. Hoerning C, Wyse DL, Chen S, Wells MS, Gesch RW and Forcella F. 2016. Influence of Winter Annual Cover Crops on Soybean Cyst Nematode Populations. ASA Paper Number 42-7
4. Forcella F, Wyse DL, and Gesch RW. 2016. Keep It Green: Ecosystem Services of Year-Round Cropping. ASA Paper Number 44-5 (Invited CCA Specialty Certification symposium presentation)
5. Forcella F, Gesch RW, Thom MD. 2016. Invited by University of Minnesota to demonstrate edible oil of winter camelina to Governor Mark Dayton and entourage from the Minnesota State Legislature. St Paul, Minnesota. April 2016.
6. Thom MD, Forcella F, and Gesch RW. 2016. Invited by University of Minnesota to demonstrate soil conserving properties of winter camelina, pennycress, and Kernza to Governor Mark Dayton and entourage from the Minnesota State Legislature. St Paul, Minnesota. April 2016.
7. Thom, M. D. July 21, 2016. Nitrogen use efficiency in cover cropping and inter-seeded soybeans. USDA-ARS NCSCRL Field Day. Swan Lake Research Farm. 100 audience members.
8. Thom, M. D. June 29, 2016. Environmental and agronomic benefits of dual cropping systems in Minnesota. University of Minnesota Magnusson Research Farm Field Day. 50 audience members.
9. Forcella F, Thom MD and Gesch RW. 2016. Invited by University of Minnesota to demonstrate edible oil of winter camelina to attendees of the annual meeting of the National Association of Conservation Districts. St Paul, Minnesota. July 2016.

10. Thom MD, Forcella F and Gesch RW. 2016. Invited by University of Minnesota to demonstrate soil conserving properties of winter camelina, pennycress, and Kernza to attendees of the annual meeting of the National Association of Conservation Districts. St Paul, Minnesota. July 2016.
11. Thom, M., C. Eberle, F. Forcella. September 24-30, 2016. Promoting environmental services using dual-purpose cover crops in the Upper Midwest. XXV International Congress of Entomology, Orlando Florida. 30 audience members.
12. Invited presentation: Forcella F, Wyse D, and Gesch R. 2016. Keep it green: Ecosystem services of year-round cropping. Plant Science Department, North Dakota State University. November 3, 2016.
13. Forcella F, Wyse D, and Gesch R. 2016. Keep it green: Ecosystem services of year-round cropping. ASA-CSSA-SSSA Symposium – IPM Resistance Management . November 7, 2016. https://scisoc.confex.com/scisoc/2016am/videogateway.cgi/id/25419?recordingid=25419
14. Invited presentation: Forcella F, Wyse D, and Gesch R. 2016. Keep it green: Cleaning up with cash cover crops. Green Land, Blue Waters Symposium, University of Missouri. November 28, 2016.
15. Thom M, et al. 2017. Reduced nutrient pollution and water runoff in a cover crop and soybean system in the Upper Midwest. UMN Production Agriculture Symposium (Increasing Cropping System Diversity While Maintaining Yield and Profit). February 22, 2017.
16. Wells MS, et al. 2017. Double cropping systems with pennycress and camelina. UMN Production Agriculture Symposium (Increasing Cropping System Diversity While Maintaining Yield and Profit). February 22, 2017.
17. Gesch R. 2017. Expert Panel. UMN Production Agriculture Symposium (Increasing Cropping System Diversity While Maintaining Yield and Profit). February 22, 2017.
18. Gesch R, et al. 2017. Winter oilseeds as cash cover crops for sustainable crop production." UMN Extension 3rd Crop Producers Meeting, Fairmont, MN, March 22nd.
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20. Moore SA, Wells MS, Hard A, Dobbratz M, Becker RL, Gesch RW and Forcella F. 2017. Double-Cropping Pennycress (Thlapsi arvense L.) with High-Value Short-Season Crops in the Upper Midwest. ASA Poster
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23. Cubins J, Wells MS, Walia MK, Wyse DL, Forcella F and Gesch RW. 2017. Influence of Harvest Date on Pennycress Phenology, Seed Yield, and Quality. ASA Poster
24. Walia MK, Wells MS, Cubins J, Wyse DL, Gesch RW and Forcella F. 2017. Influence of Harvest Date on Winter Camelina Phenology, Seed Yield, and Quality. ASA Poster

25. Dose HL, Gesch RW, Forcella F, Aasand K, Johnson BL, Steffl N, Wells MS, Patel S, Lenssen AW and Berti MT. 2017. Intensifying Production in the Northern Corn Belt By Incorporating Cash Cover Crops. ASA Paper
26. Hoerning C, Wyse DL, Wells MS, Gesch RW and Forcella F. 2017. Oilseed Cash Cover Crops Enhancing Productivity and Profit in Corn-Soybean Rotations. ASA Paper

7. References cited

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Williams, S.M., and R.R. Weil. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68:1403-1409.

Attachment 1:

DRAFT Manuscript intended for Submission to the Agronomy Journal

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Winter camelina and pennycress as nitrate-sequestering cash cover crops

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Abstract

Water resources in the Upper Midwest have been compromised by excessive levels of nitrate. At least some of this nitrate emanates from agricultural sources. In particular, cropped fields are highly susceptible to nutrient losses during overwinter fallow periods. Autumn-sown winter cover crops were tested for their abilities to (1) be relay-cropped with soybean, (2) sequester N in plant biomass, and (3) deplete soil residual nitrate levels. Cover crops tested were winter rye (*Secale cereale*), forage radish (*Raphanus sativus*), and the two oilseed crops, winter camelina (*Camelina sativa*) and pennycress (*Thlaspi arvense*). They were evaluated in a relay crop production system with soybean (*Glycine max*) at three sites spanning the north-south climatic gradient of Minnesota and were compared to traditional overwinter fallowed tilled and no-tilled soybean systems. Forage radish and winter rye sequestered the most N in autumn, but much was released in spring in winter-killed radish. Both camelina and pennycress survived winter well, grew vigorously in spring (May-June), sequestered 73 to 174 kg N ha^{-1}, and typically lowered residual soil nitrate levels. Aggregate seed yields often were higher for relayed crops (oilseed + soybean) than for soybean alone (tilled and no-tilled treatments). Estimated gross revenues for the relayed crops sometimes were higher, but never lower, than the tilled or no-tilled

soybean. Consequently, winter camelina and pennycress may be considered viable cash cover crops for the Upper Midwest that may generate income for growers and also protect agricultural fields from nitrate losses, especially in spring.

Introduction

Summer annual grain crops only protect the soil for a few months of each year. Soils in these systems erode at much higher rates than soils under perennial grassland or woodland vegetation (Lubowski et al., 2006; Tilman et al., 2002). A quarter of the world's agricultural soils are either highly degraded or are rapidly becoming so (FAO 2011). These exposed soils facilitate runoff and leaching of nutrients, which is a major cause of water pollution (Randall et al., 1997). A conservative estimate of external costs solely related to damage to soil and water resources in the United States from conventional agriculture is $2.6 billion annually (Tegtmeier and Duffy 2004).

The most severe water pollution in Minnesota is in the southern half of the state, and the primary cause is contamination from croplands (MPCA 2014). MPCA also determined that 75,000 MT of nitrogen (N) annually flow into the Mississippi River in Minnesota. The fate of much of this N is in the Gulf of Mexico where it is a primary cause of algae blooms (Rabalais et al., 2007). The MPCA has set a goal to reduce nutrient loading by 20% by 2025 and 45% by 2040 (MPCA 2014). To reach these goals, improvements in fertilizer efficiency and drainage tile line management may not be sufficient; widespread adoption of cover crops, which sequester soil nutrients, may be necessary.

Much of the cover crop research in the Upper Midwest has involved winter cereals (Kladivko et al. 2004, Kaspar et al. 2012, Strock et al. 2004, McCracken et al. 1994). Winter rye, winter wheat (*Triticum aestivum*), and similar crops performed well as cover crops in the Central and Southern US (McKibben and Pendleton 1968, McCracken et al., 1994), but Minnesota farmers have been reluctant to adopt cover cropping (Census of Agriculture 2012). Indeed, only about 2% of Minnesota cropland is planted with any type of cover crop (USDA Census of Agriculture 2012). A likely reason for this is that winter rye does not mature in time to be harvested for grain in Minnesota before the annual summer crops must be planted, so it typically is killed chemically in April or May by Minnesota growers who use it as an over-winter cover crop (Wyse 1994). Since winter rye provides little, if any, direct income to growers in Minnesota, other winter annual crops have been investigated for their ability to offer financial returns for Minnesota growers. The integration of traditional summer annual grain crops with new winter annual oilseed cover crops, such as pennycress and winter camelina, has the potential to lessen environmental problems (i.e., improve water quality) while maintaining or increasing economic viability of farms.

Interest in pennycress as an oil source within the United States began in 1944 due to a sharp drop in vegetable oil supply, as previously 90% of rapeseed (*Brassica* spp.) oil had been imported from Japan (Clopton and Triebold 1944). Interest seemed to wane after World War II, but was renewed when the importance of cover crops for soil health and water quality was demonstrated. Best and McIntyre (1975) reported seed yield of pennycress, as did Mitich (1996). Unlike pennycress, winter camelina has been grown for centuries starting in the late Neolithic age in Eastern Europe and Western Asia, and as a result, it is more domesticated than pennycress as an oilseed crop (Vollmann and Eynck 2015). The oil profiles from both pennycress and winter camelina seeds have been analyzed for industrial and food quality (Clopton and Triebold 1944, Moser 2009, Moser 2010). Due to high glucosinolate and erucic acid contents, pennycress oil is not USDA-approved for human or livestock consumption, while the high omega-3 fatty acid and tocopherol content in winter camelina facilitated USDA approval for both food and feed (Food and Drug Administration, 2016). Both pennycress and winter camelina have high rates of winter survival in the Upper Midwest, as well as maturation in June (Gesch and Cermak, Johnson et al. 2015). These traits permit soybean and other short-season crops to follow their harvest, which allows double-cropping and net economic benefits (Phippen and Phippen, 2012 and Gesch et al., 2013). So far, most of the research on double-cropping with pennycress has used the sequential planting method, where soybean is planted after pennycress harvest (Phippen and Phippen 2012, Johnson et al., 2015). For winter camelina, however, researchers have found the relay planting method to be the most productive, where soybeans are inter-seeded into the standing cover crop at around the same planting time recommended for soybean in the region (Gesch et al., 2014, Berti et al., 2015). The relay planting method was used for both pennycress and winter camelina for the research discussed here.

The objectives of the study were to determine (1) levels of N and P sequestration by plant uptake, (2) levels of soil residual levels of N and P, and (3) the productivity and economics of relay cropping winter oilseeds with soybean across three diverse environments in Minnesota.

Materials and Methods

Experimental Sites and Crop Operations. The study was conducted from August 2014 to October 2016, spanning two complete growing seasons for both the winter and summer annual crops at three research sites: (1) the UMN Magnusson Research Farm, 7 km NW of Roseau, MN 48˚52' N 95˚50' W, on a Zippel very fine sandy loam with a maximum calcium carbonate content of 30%; (2) the USDA Swan Lake Research Farm, 24 km NE of Morris, MN 45˚35'N 95˚54' W, on a Barnes loam with a maximum calcium carbonate content of 30%; and (3) the UMN Southern Research and Outreach Center less than a kilometer southwest of Waseca, MN 44˚04' N 93˚31' W, on a Webster clay loam with a maximum calcium carbonate content of 20%. These sites represented a gradient in temperature and precipitation across the state of Minnesota, with annual averages for Roseau, Morris and Waseca of 2.5, 5.8, and 7.1°C, and 53, 67, and 91 cm, respectively.

There were four autumn-planted cover crop treatments, a tilled winter fallow control, and a no-tilled fallow control with spring wheat stubble (simply "stubble" hereafter) placed in randomized complete block experimental designs that included four blocks at each site-year. The four cover crop treatments were winter rye, an improved forage radish variety called Tillage Radish ('Daikon', hereafter radish), winter camelina ('Joelle'), and pennycress ('Beecher Farms'). Plots were 3m by 9.1m, in which 12 rows of cover crops and later 4 rows of soybean were planted.

Cover crops were sown in 25 cm spaced rows in early autumn into spring wheat stubble with a small no-till drill (Plotter's Choice, Kasco Manufacturing, Shelbyville, IN). Seeding rates and dates are given in Table 1. Winter camelina and pennycress at all sites were fertilized by broadcasting 80-30-30 kg ha^{-1} N-P-K after the late April or early May soil sampling date This fertility regime has been found beneficial for optimizing winter oilseed development and yield in a relay cropping system (Gesch and Cermak 2011; Gesch et al. 2014). Soybeans were sown in 76 cm spaced rows into growing winter camelina and pennycress that were beginning to bolt, into standing winter rye that was killed with glyphosate (1.1 kg ae ha^{-1}), and into fallow plots for the other treatments (Table 1). Soybean varieties were chosen for maturities that matched the locations; they were: 1) Pioneer 91Y70 (RM10) in Waseca, 2) Pioneer P09T74R2 (RM09) in Morris, and 3) Pioneer P01T06R (RM01) in Roseau.

Soil Nutrient Analyses. Soil samples at depths of 0-30 cm and 30-60 cm were collected five times during each growing season of the study: (1) before planting cover crops in early autumn, (2) after planting cover crops in the last two weeks of October, (3) before planting soybean in late April to early May, (4) after the harvest of winter camelina and pennycress in late June to early July, and (5) after soybean harvest in late September to early October. Soil cores were 2.5 cm diameter, 10 cores were taken in each plot, cores were distributed in a diagonal manner within plots, and they were aggregated subsequently within plots prior to chemical analyses. Samples were dried, ground to pass through a 40 mesh sieve, and subsamples analyzed for ammonium and nitrate N and P content using the procedures outlined by Mulvaney (1996) for N and Olsen and Sommers (1982) for P.

Crop Analyses. Cover crop biomass (aboveground) was sampled three times each year of the study: (1) after cover crop establishment in the last two weeks of October, (2) while winter annual cover crops were bolting in late April to mid-May, and (3) during anthesis of the oilseed cover crops in late May to early June. Cover crop biomass samples were 0.5 m in length from two central rows. In addition to dry matter, the samples were analyzed for percent N and C using a Leco CN-2000 combustion analyzer (Leco Corporation, St. Joseph, MI).

Soybean biomass was sampled near its peak in mid to late August, as leaves began to senesce. Samples were 0.5 m in length and were taken from the two central rows of each plot. Within these samples, the number of pods of three plants in each row were recorded. Both cover crop and soybean biomass samples were weighed as soon as possible to determine fresh weight and then oven-dried for 48 h at 65°C before determining the dry weight.

Crop heights were recorded weekly until the oilseeds were harvested, and then every other week throughout the rest of the growing season. One representative cover crop plant was measured from each of the ten central rows of the cover crop treatments, and two representative soybean plants were measured from the two central rows for all plots.

Photosynthetically active radiation (PAR) available to soybean underneath the winter camelina and pennycress canopies was quantified using a PAR ceptometer (LP-80, Decagon Devices, Pullman, WA). The center of the ceptometer was placed under the oilseed cover crop canopy and directly over and perpendicular to a soybean row. Five readings were taken in this manner at 10 cm intervals, and the mean was recorded. Immediately following the fifth PAR reading below the oilseed canopy, the ceptometer was held above the canopy and three readings were taken and averaged to determine above canopy PAR.

Winter camelina, pennycress, and soybean yields for this study were determined by collecting one-meter long samples from the central two rows of each plot. Samples were collected when >90% of the crop senesced. The samples were threshed with a Wintersteiger Model 160 plot combine when available, otherwise they were threshed by hand using a Seedburo 8Y 6/64" seed sieve. Winter camelina and pennycress seed weights were standardized to a moisture content of 100 g kg^{-1}, and soybean seed weights were standardized to a moisture content of 130 g kg^{-1}. When available, a grain moisture meter (Dickey-John GAC 2100AG) was used to determine seed moisture content, otherwise seeds were oven-dried at 80° C for 48 h or to constant weight to determine dry weight.

Growing degree days were calculated for all crops. Base and ceiling temperatures were 4° and 30°C for the cover crops and 10° and 30°C for soybean.

Statistical Analyses. All statistical analyses included a standard ANOVA test of significance at the P = 0.05 level unless otherwise noted. Tukey's Honest Significant Difference was used to compare treatment means. These procedures were performed using R version 3.3.2.

Results and Discussion

Weather. Weather and climate data are summarized in Table 2. Autumn (September + October) temperatures in Waseca and Morris were nearly identical and higher than those in Roseau both years. Autumn precipitation in Waseca and Roseau was appreciably higher both years compared to Morris. Spring (April-June) temperatures followed expected trends, with those in Waseca slightly exceeding those in Morris, and appreciably exceeding those in Roseau. Spring precipitation was consistently high in Waseca (≥ 266 mm); very low in Morris (149-207 mm), especially in April and June; and relatively low in

Roseau (191-242 mm). Summer (July-September) precipitation was high both years in Waseca (489-900 mm), critically low in Morris (191-321 mm), and relatively low in Roseau (286-233 mm), given its lower temperatures and evaporative demand than the other sites. Consequently, plants at Morris likely were impacted by abnormally dry conditions, which likely affected yields. In general, Waseca had the wettest environment followed by Roseau and then Morris.

Oilseed Yields. The range in camelina yields across locations and years was 791 kg ha^{-1} (Roseau 2015) to 1502 kg ha^{-1} (Waseca 2015), while pennycress yields ranged from 1238 kg ha^{-1} (Morris 2015) to 2063 kg ha^{-1} (Roseau 2015). Morris had the highest mean yield across years for camelina, while Roseau had the highest for pennycress (Figure 1). Camelina seed yields fit within the range for the area surrounding Morris reported by Gesch et al. (2013, 2014) and Berti et al. (2015). Likewise, the pennycress seed yields fit within the range for the area surrounding Ames, Iowa reported by Marek et al. (2008) and Johnson et al. (2015).

Soybean Yield. The range in soybean yield across all site years was 443 kg ha^{-1} (Roseau 2015 relayed into pennycress) to 4596 kg ha^{-1} (Waseca 2016 relayed into camelina). For three of the six site-years, plots with soybean relay-cropped with pennycress had significantly lower yields than those in the fallow, radish, and rye treatments. For two site-years, plots with soybean relay-cropped into camelina had significantly lower yields than those in the fallow treatments, but were never significantly different from those in rye (Figure 1). Relatively low plant densities of the oilseed cover crops in Waseca during the 2016 growing season (Table 3) may explain why there were no significant differences in soybean yields among treatments there.

Combined Oilseed and Soybean Yield. When winter oilseed and soybean yields were aggregated, the total seed yield was consistently greater compared to the other treatments, although this was not always statistically significant (Figure 1). The most pronounced instances where aggregated oilseed and soybean yield was greater than the soybean yield from other treatments was in Roseau in both years of the study. The aggregate seed yield of camelina and soybean in Roseau during the 2016 growing season was significantly greater than the soybean seed yield from the no-till fallow treatment, and both pennycress and camelina aggregated with soybean in Waseca in 2016 yielded significantly more seed than that produced from the tilled treatment.

The price of canola was used to estimate the price of winter camelina and pennycress since there is not currently an established market price for these oilseed crops (Gesch et al. 2014). This approach was also used here to represent the potential income to growers of the various cropping systems as accurately as possible (Table 4). For a full accounting of inputs and net returns for both winter camelina and soybean crops, see Gesch et al. (2014). A complete economic analysis was beyond the scope of this study, but standardizing the yield results by an appropriate grain price can present a clearer outlook of the potential economic value of an oilseed-soybean relay-cropping system compared to other cropping systems.

Relay-cropping systems with oilseeds and soybean, which result in significantly higher yield, do not automatically result in significantly higher gross income. This is because the commodity price of soybean is often slightly higher than that for the commodity price of canola and, by extension, winter camelina and pennycress. For the 2015 Waseca site-year, no significant difference occurred among treatments, but worth noting is that ANOVA ($P<0.05$) showed that at least one treatment was significantly different from another treatment (Table 4). There were no significant differences in net income among treatments in Morris. Spring precipitation in Morris was abnormally low in April 2015 and in June in both years, which likely resulted in water stress of both oilseeds and soybean. Since pennycress yielded particularly well in Roseau, this was enough to over-compensate for any yield penalties it inflicted upon soybean in 2015. Though there were no significant differences in 2016 in Roseau, the pennycress-soybean relay-cropping system has potential to bring growers more income than other systems involving soybean. The general pattern of cover crop success highlighted by this study is that growing pennycress and soybean rather than soybean alone may provide higher returns to growers in regions surrounding Roseau and Waseca. At least for years with climates mirroring those of this study, camelina and soybean may provide about the same amount of income as soybean alone in the regions surrounding Morris and Roseau. Other studies, however, have found that camelina and soybean can yield more than mono-cropped soybean near Morris, especially when a “skip-row” planting system is used (Gesch et al. 2013, 2014, Berti et al. 2015).

Biomass and Nitrogen. Crop biomass, percent N in biomass, and the amount of sequestered N (kg ha^{-1}) results are shown in Table 3. In autumn, the order of biomass production tended to be radish, winter rye, camelina, and pennycress. Radish produced up to 3300 kg ha^{-1} of aboveground material in autumn, followed by winter rye, winter camelina, and pennycress with maximum values of nearly 1900, 1400, and 900 kg ha^{-1}, respectively. In all six site-years radish produced significantly more biomass than winter camelina, and in five site-years it produced significantly more than pennycress. Winter rye consistently produced higher biomass than both camelina and pennycress in autumn, but was never statistically different than camelina. Winter rye produced significantly more biomass in autumn than pennycress in four of the six site-years.

The N concentration in aboveground biomass randed from about 2.5 to 4% in autumn. However, no consistent differences occurred among cover crops in concentration of N in either year. The only significant differences were in Waseca and Morris in 2016, where N in radish was significantly lower. Otherwise, the amount of N sequestered in aboveground biomass by each cover crop in autumn tracked nearly exactly the amount of biomass production. Values ranged up to 140 kg N ha^{-1} for radish, to 77, 48, and 35 kg N ha^{-1} for winter rye, winter camelina, and pennycress, respectively.

April biomasses tended to be highest for winter rye, with a maximum value of about 2500 kg ha^{-1}, followed by pennycress and winter camelina with high values of about 1700 and 2300 kg ha^{-1}, respectively. (Radish winter-killed.) Biomass of winter rye in the spring was significantly greater than that of camelina in both Waseca and Roseau, but there was no significant difference amongst these covers in Morris for either year (Table 3). Only in Waseca did winter rye produce significantly more biomass than pennycress by April.

By April, N percentage in the aboveground biomass shifted and varied significantly. Winter camelina had a significantly higher percentage of N in all six-site years compared to winter rye, while for pennycress, five site-years showed a higher percentage than winter rye (Table 3). This result manifests itself in the amount of N sequestered by each cover crop in the spring.

Highest level of sequestered N in April was 83 kg ha^{-1} in pennycress, followed by 67 in winter rye and 59 kg ha^{-1} in winter camelina. Though winter rye biomass production was significantly greater than that for winter camelina in Waseca and Roseau, there were no significant differences for any site-year with regard to the amount of N sequestered. Biomass production compensated for N concentration in the case of winter rye versus pennycress in Waseca in 2015, as the amount of N sequestered was significantly greater for winter rye. However, this was not the case in Waseca in 2016, where there was no significant difference between pennycress and winter rye in sequestered N. Since winter rye did not reach peak biomass before soybean planting, and forage radish did not survive the winter, the total amount of N that winter camelina and pennycress sequestered was often 2-3 times greater than these other crops.

During May/June biomasses of winter camelina and pennycress never differed. Lowest to highest values ranged from about 3000 to nearly 6000 kg ha^{-1}. Percent N and amount of N sequestered also did not vary between cover crops. Values ranged from 2 to about 3.5% for percent N and 89 to 174 kg N ha^{-1} sequestered in aboveground biomass. These latter values are appreciable, and represent the high potential for winter oilseeds to hold N in plant tissues at a time of the year when N is highly susceptible to leaching Randall et al. 1995).

Canopy Light Penetration and Soybean Development. Photosynthetically active radiation (PAR) available to soybean seedlings underneath the winter camelina and pennycress canopies nearly always was greater for winter camelina than for pennycress (Figure 2). Thus, in a relay-cropping system, soybean seedlings planted into winter camelina received more light than when planted into pennycress. With relatively less light reaching soybean seedlings under the pennycress and winter camelina canopies early in the primary growing season, potential for soybean etiolation and lodging increases, which may result in reduced yields. In Waseca and in Roseau for both years of the study, the soybean seedlings in pennycress and winter camelina plots were taller on average than those of other treatments (Figure 3). The first two weeks in June appear to be the period in which soybean seedlings etiolated in Waseca, which was more pronounced under the pennycress canopy. This window of etiolation in Roseau appeared to be the last two weeks in June and into the first week of July. Additionally, there was a point in each site-year in which soybean plants relay-seeded into pennycress and winter camelina became dwarfed by soybean plants seeded in the other treatments. This likely contributed to the reduced soybean yields that followed either pennycress or winter camelina in four of the six site-years.

The soybean aboveground biomass observations followed the same patterns as those of soybean yield (Figure 4A). Biomasses of soybean following winter camelina and pennycress were lower than those in other treatments, especially in Morris where lack of rain likely contributed to soybean stress. Interestingly, the number of pods per plant was relatively consistent regardless of treatment (Figure 4B), which suggests that differential pod fill was influenced by treatments and would help explain differences in soybean yields across treatments.

Soil Nitrogen Levels. Soil NO_3-N levels in the 0-30 cm and 30-60 cm depths are presented in Table 5. By the October of both years, all of the cover crop treatments were well established, except at Waseca in 2015, where inclement weather delayed cover crop planting. At that time soil NO_3-N varied greatly among treatments and sites, ranging from 4 to 22, 6 to 29, and 7 to 54 kg ha^{-1} at Waseca, Morris, and Roseau, respectively, in the top 30 cm of soil. Levels usually were less at 30 to 60 cm soil depths. Nitrate levels generally were lower for the radish treatment than for the fallow treatments, which reflected appreciable uptake by the radish plants during autumn. The pennycress treatment was not statistically different than the fallow treatments in autumn for 5 of the 6 site-years, whereas the winter camelina treatment had statistically lower NO_3-N levels for 3 of the 6 site-years. The winter rye treatment had significantly lower mean NO_3-N levels in only 2 of the 6 site-years compared to the fallow treatments.

When the oilseed cover crops were flowering in late April, nitrate levels at 0-30 cm still varied (5-39, 8-37, and 7-88 kg ha-1 in Waseca, Morris, and Roseau, respectively). However, at this time the levels of nitrate typically were lower in the treatments with winter-hardy cover crops than the other treatments. Indeed, for the winter camelina treatment, there were five site-years where nitrate was lower than in fallow, for pennycress there were four such site-years, and for winter rye there were five such site-years.

Because soil NO_3-N was often lower in winter hardy cover crop treatments compared to the fallow control, while radish and control treatments were often similar, there is evidence that cover crop treatments that grew at least until soybean planting, were likely more effective than radish in sequestering NO_3-N. Our data on N sequestered in cover crop biomass support these soil NO_3-N observations. The forage radish sequestered the most N in autumn at each site, which directly corresponds to low levels of NO_3-N in the soil under this treatment. Likewise, in the spring, the three remaining cover crops often sequestered similar levels of N, and soils with the least amount of NO_3-N at this time were under these treatments. Kaspar et al. (2007) observed that a winter rye cover crop reduced the NO_3-N load in water drained from tile lines by 61% (31 kg N ha^{-1}) compared to a fallow control. Other studies have observed a similar pattern of winter rye cover crops reducing NO_3-N concentration in ground water (Strock et al. 2004, Qi et al. 2011, Kaspar et al. 2012).

After cover crop harvest in late June/early July, mean soil NO_3-N levels tended to be similar between the winter fallow and cover crop treatments. Fertilizer application of 80 kg N ha^{-1} to winter camelina and pennycress treatments in April likely facilitated this leveling effect.

Since there has been extensive research into questions about the extent to which winter rye captures N and P, comparisons between winter rye and the oilseed crops in this study can provide an estimate of how well these new crops may be able to perform in this regard. Averaging sites and years and considering only the sampling dates for which living winter rye was present, this treatment had 11% less soil NO3-N at a depth of 0-30 cm than the winter camelina treatment, and 22% less than the pennycress treatment. At a depth of 30-60 cm, the winter rye treatment had 16% less than the winter camelina treatment, and 34% less than the pennycress treatment. However, with averages calculated in the same manner, winter camelina and pennycress sequestered 27% and 24% less N than winter rye, respectively. Importantly though, the rye is purposefully killed in spring, whereas the oilseeds continue to accumulate biomass through May and June. Because these oilseeds remain on the landscape much longer than winter rye, they may compensate for this reduced autumn-winter N sequestration by abundant uptake of N in May and June. This provides some indicator of the general performance of each oilseed cover crop compared to winter rye in terms of NO_3-N capture.

Following soybean harvest in late September/early October, all treatments had similar NO_3-N levels in the 0-30 cm soil profile. There was only one site year with a significant difference, in which the pennycress treatment had a lower soil NO_3-N content than the tilled winter fallow treatment for the Morris 2016 site-year. Trends in NO_3-N by cropping treatment at the 30-60 cm depth were generally similar to those for the 0-30 cm depth.

Spring through early summer is a critical window of time in which the potential for N leaching is higher than almost any other time throughout the year. Though pennycress soil NO_3-N levels at a depth of 30-60 cm were equivalent as those of the fallow treatments in April, by late June/early July these levels had fallen significantly below those of the fallow treatments. This decrease in soil NO_3-N levels from April through early summer did not occur in radish treatments. Pennycress likely scavenged N during this time, whereas winter-killed radish could not. These data indicate that there is a general pattern of elevated NO_3-N levels in soils sampled in spring or early summer in which radish had been planted the previous fall. This pattern is discernable for 7 of the 12 observations. Forage radish has been shown to release part of the N it sequestered during autumn to groundwater at depths below annual crops' root zones in spring on coarser textured soils (Dean and Weil 2009). This research also showed that in the spring, even on finer textured soils, N levels were elevated in shallow depths of these soils in plots where forage radish had been grown relative to other cover crops such as winter rye and rape. Some of this N could also potentially escapes the root zone of summer annual crops as their root systems are not fully established by this time.

Conclusions

Cover crops must meet two requirements to be considered viable options for most growers in the Upper Midwest: (1) The cover crop must provide enough of a financial return to be considered worth the time and effort to grow. (2) The cover crop must provide a substantial agroecosystem service, such as improving soil and water quality characteristics. This research demonstrates evidence that winter camelina and pennycress deliver both financial return and ecosystem services (enhanced nitrate uptake) and, thus, may be cover crops that will garner widespread acceptance among growers in the region. Each crop may have its own niche based upon climate, soil, and economics. For instance, it appears that pennycress thrives in Roseau (cooler), while winter camelina thrives in Waseca (warmer). As breeding for each of these crops continues at the University of Minnesota, further improvements in their deliverables is expected.

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Table 1 Summary of Crop Operations and Specifications

Crop	Year	Seeding Rate	Planted Depth	Planting/Removal Date: Waseca	Planting/Removal Date: Morris	Planting/Removal Date: Roseau	Removal Method
Radish	2014/15	11 kg ha^{-1}	1.3 cm	5 Sep/NA	2 Sep/NA	28 Aug/NA	Winter Killed
	2015/16			22 Sep/NA	31 Aug/NA	3 Sep/NA	
Winter Rye	2014/15	76 kg ha^{-1}	1.3 cm	5 Sept/27 Apr	2 Sep/1 May	28 Aug/4 Jun	Glyphosate Application
	2015/16			22 Sep/5 May	31 Aug/22 Apr, 16 May	3 Sep/17 May	
Winter Camelina	2014/15	6.7 kg ha^{-1}	0.6 cm	5 Sep/18 Jun	2 Sep/2 Jul	28 Aug/2 Jul	Harvested
	2015/16			22 Sep/23 Jun	31 Aug/23 Jun	3 Sep/7 Jul	
Pennycress	2014/15	6.7 kg ha^{-1}	0.6 cm	5 Sep/18 Jun	2 Sep/23 Jun	28 Aug/1 Jul	Harvested
	2015/16			22 Sep/21 Jun	31 Aug/16 Jun	3 Sep/7 Jul	
Soybean	2015	444,800 seeds ha^{-1}	2.5 cm	24 Apr/2 Oct	30 Apr/15 Sep	5 May/6 Oct	Harvested
	2016			3 May/6 Oct†	22 Apr/19 Sep‡	17 May/3 Oct	

†For one block, soybean was harvested on 13 Oct for these treatments: No-Till, Tilled, Winter Rye, Radish

‡For all blocks, soybean was harvested on 29 Sep for the pennycress and winter camelina treatments

Table 2

	Mean Air Temperature (˚C)			Accumulated GDD (4/30˚C d) Oilseed		Accumulated GDD (10/30˚C d) Soybean		Total Precipitation (mm)		
Month	2014 2015	2015 2016	30 Year Normal	2014 2015	2015 2016	2014 2015	2015 2016	2014 2015	2015 2016	30 Year Normal
Waseca, MN										
Sept.	16	20	16	359	476	187	296	59	149	93
Oct.	9	11	9	149	211	24	59	35	31	68
Apr.	9	9	8	150	169	41	53	70	50	82
May	14	15	15	323	342	149	172	121	95	100
Jun.	20	21	20	483	513	303	333	194	121	119
Jul.	21	23	22	539	572	353	386	188	227	112
Aug.	20	22	21	489	560	303	374	152	297	121
Sept.	20	19	16	476	456	296	276	149	376	93
Morris, MN										
Sept.	16	19	15	347	449	172	269	17	32	74
Oct.	9	11	7	155	204	37	50	9	38	64
Apr.	8	7	7	146	133	42	43	20	52	59
May	14	15	14	309	340	143	167	149	43	72
Jun.	20	20	19	488	481	308	301	38	54	102
Jul.	22	21	21	550	535	364	349	74	184	99
Aug.	20	21	20	498	521	312	335	85	94	85
Sept.	19	17	15	449	380	269	201	32	43	74
Roseau, MN										
Sept.	14	16	13	284	358	119	184	58	36	62
Oct.	7	8	5	116	120	29	20	28	49	46
Apr.	6	3	4	103	58	15	5	10	31	35
May	11	14	12	228	304	93	140	95	78	70
Jun.	18	18	17	408	405	228	225	86	133	107
Jul.	21	20	20	516	497	330	311	135	85	84
Aug.	19	19	19	445	462	259	276	115	50	78
Sept.	16	14	13	358	58	184	135	36	98	62

Table 3. Cover crop above ground biomass, percentage N, and sequestered N (biomass x %N).

		Waseca			Morris			Roseau		
		Above Ground		Sequestered	Above Ground		Sequestered	Above Ground		Sequestered
Month/Yr		Biomass (kg ha^{-}	%N	N (kg ha^{-1})	Biomass (kg ha^{-1})	%N	N (kg ha^{-1})	Biomass (kg ha^{-1})	%N	N (kg ha^{-1})
Sept./Oct. 2014	Tillage Radish®	2105 a	2.6 a	55 a	1376 a	3.1 a	43 a	3372 a	4.2 a ‡	140 a †
	Winter Rye	1883 a	2.9 a	54 a	1105 ab	3.1 a	34 ab	1759 b	4.4 a ‡	77 b †
	Winter Camelina	1393 ab	2.5 a	32 b	651 bc	3.4 a	22 bc	1374 bc	3.5 a ‡	48 bc †
	Pennycress	841 b	2.3 a	19 b	316 c	3.0 a	9 c	912 c	4.0 a ‡	35 c †
Apr. 2015	Winter Rye	1444 a	3.6 c	52 a	1026 a ‡	3.3 b	35 a	2414 a	2.8 b	67 a ‡
	Winter Camelina	892 b	4.5 a	40 ab	699 a ‡	5.5 a	38 a	1141 b	4.2 a	44 a ‡
	Pennycress	656 b	4.1 b	27 b	1353 a ‡	4.7 a	63 a	1923 ab	4.4 a	83 a ‡
May/Jun. 2015	Winter Camelina	5798 a	3.0 a ‡	172 a	4347 a	3.5 a	153 a	3709 a	3.6 a	174 a
	Pennycress	5313 a	2.4 a ‡	126 a	4823 a	2.9 a	138 a	5276 a	3.4 a	131 a
Sept./Oct. 2015	Tillage Radish®	140 a	3.3 b	5 a	1861 a	2.7 b	51	508 a	3.4 a	18 a
	Winter Rye	83 ab	3.7 ab	3 ab	898 b	4.1 a	36	391 ab	4.0 a	15 ab
	Winter Camelina	54 b	4.0 a	2 b	403 bc	4.7 a	19	162 b	4.1 a	6 b
	Pennycress	36 b	4.0 a	1 b	164 c	4.4 a	7	272 ab	3.2 a	8 ab
Apr. 2016	Winter Rye	1202 a	3.0 b	37 a	2497 a	2.4 b	58 a	2546 a	1.4 b	36 a
	Winter Camelina	702 b	4.6 a	32 a	1701 a	3.5 a	59 a	456 b	4.9 a	23 a
	Pennycress	571 b	4.8 a	27 a	2343 a	2.7 ab	64 a	1120 ab	3.8 a	38 a
May/Jun. 2016	Winter Camelina	4980 a	2.4 a	124 a	5896 a	2.7 a	160 a	4524 a	2.0 a	89 a
	Pennycress	2888 a	2.5 a	73 a	5209 a	2.5 a	131 a	4149 a	2.7 a	110 a

† indicates assumptions of ANOVA were not met

‡ indicates significance at the P<0.1 level

Table 4. Comparison of combined soybean and oilseed gross revenue based upon plots containing various cover crop treatments.

	Waseca		Morris		Roseau	
	2015	2016	2015	2016	2015	2016
Cover Crop Treatment			$\$ha^{-1}$			
None: Till	1662a	1682b	1398a	1470a	451b	964a
Stubble	1649a	1790ab	1342a	1485a	NA	799a
Radish	1742a	1793ab	1309a	1386a	466b	850a
Rye	1675a	1763ab	1310a	1266a	473b	960a
Camelina	2027a	2155ab	1353a	1302a	589b	935a
Pennycress	2007a	2251a	1413a	1057a	908a	1364a

2016 Calendar Year Mean Soybean Price: $406/Mg
2016 Calendar Year Mean Canola Price: $353/Mg
Values within columns followed by the same letter are not significantly different. Analyzed using Tukey's HSD.

Table 5. Soil NO_3-N levels from soil samples taken at depths of 0-30 cm and 30-60 cm in various cover cropping treatments.

Soil NO3-N Levels Scaled into Units of kg ha^{-1}													
		Soil Core Depth: 0-30cm						Soil Core Depth: 30-60cm					
Month/ Year	Cover Crop Treatment	Waseca		Morris		Roseau		Waseca		Morris		Roseau	
Oct 2014 Year 1	None: Tilled	6.1 bc	†	28.5 a	‡	54.4 a	§	5.9 bc		1.1 a	†#	28.4 a	
	Wheat Stubble	22.4 a	†	28.2 a	‡	NA		11.2 a		1.0 a	†#	NA	
	Forage Radish	3.7 c	†	6.5 b	‡	6.8 b	§	4.1 c		0.6 a	†#	4.7 b	
	Winter Rye	4.9 c	†	15.5 ab	‡	17.0 ab	§	4.9 c		1.1 a	†#	8.8 b	
	Winter Camelina	4.9 c	†	12.9 ab	‡	24.4 b	§	5.0 c		0.9 a	†#	11.9 b	
	Pennycress	13.2 ab	†	14.1 ab	‡	54.4 a	§	10.3 ab		0.8 a	†#	15.8 b	
Apr 2015 Year 1	None: Tilled	14.2 a		26.7 a	†	88.2 a	†	11.0 ab	†	13.5 a		25.0 a	
	Wheat Stubble	12.3 ab		32.3 a	†	NA		14.8 a	†	13.1 a		NA	
	Forage Radish	12.5 ab		20.2 ab	†	29.4 b	†	10.1 ab	†	5.8 a		13.3 ab	
	Winter Rye	4.7 c		8.4 c	†	11.4 b	†	3.0 c	†	5.8 a		7.0 b	
	Winter Camelina	4.7 c		12.1 bc	†	28.7 b	†	4.8 bc	†	7.4 a		15.4 ab	
	Pennycress	6.2 bc		11.9 bc	†	26.0 b	†	10.7 ab	†	5.6 a		19.2 ab	
Jun/Jul 2015 Year 1	None: Tilled	19.0 ab		19.4 NS	‡	69.8 a		17.6	‡	25.0 a	‡¶	75.4 a	§
	Wheat Stubble	17.2 ab		20.9	‡	NA		12.6	‡	13.7 ab	‡¶	NA	
	Forage Radish	13.7 b		19.8	‡	51.0 ab		15.2	‡	14.3 ab	‡¶	27.3 b	§
	Winter Rye	12.4 b		19.7	‡	20.8 c		13.0	‡	7.3 bc	‡¶	2.8 c	§
	Winter Camelina	20.2 ab		27.2	‡	26.0 bc		9.3	‡	9.9 ab	‡¶	17.7 b	§
	Pennycress	35.7 a		22.9	‡	21.0 c		10.1	‡	4.4 c	‡¶	16.2 b	§
Oct 2015 Year 1	None: Tilled	24.2 NS	¶	14.4 NS		56.8 a	†	10.6	†¶	6.7 a		18.0	
	Wheat Stubble	27.5 NS	¶	10.8 NS		NA		6.4	†¶	3.6 b		NA	
	Forage Radish	29.1 NS	¶	12.3 NS		38.8 ab	†	8.0	†¶	4.3 ab		19.0	
	Winter Rye	27.5 NS	¶	13.8 NS		15.5 bc	†	7.2	†¶	4.2 ab		6.4	
	Winter Camelina	16.7 NS	¶	13.7 NS		11.4 c	†	4.4	†¶	4.6 ab		12.7	
	Pennycress	22.9 NS	¶	13.2 NS		14.5 bc	†	3.9	†¶	6.7 a		18.7	
Oct 2015 Year 2	None: Tilled	9.6 NS	†	29.1 a	†	15.6 a	‡	3.0	†	10.2 a		7.7	
	Wheat Stubble	14.8 NS	†	21.8 a	†	12.3 ab	‡	2.4	†	7.7 a		4.0	
	Forage Radish	10.2 NS	†	6.4 b	†	6.6 c	‡	5.3	†	2.8 b		5.3	
	Winter Rye	9.4 NS	†	14.0 ab	†	6.8 bc	‡	3.1	†	8.1 a		7.1	
	Winter Camelina	10.4 NS	†	24.6 a	†	7.1 bc	‡	3.0	†	10.1 a		6.1	
	Pennycress	11.3 NS	†	16.0 ab	†	9.1 bc	‡	3.6	†	8.4 a		10.0	
Apr/May 2016 Year 2	None: Tilled	39.0 NS		37.4 a		17.0 a		20.0 a		15.7 a	†	5.8 a	†
	Wheat Stubble	30.8 NS		33.8 a		13.4 ab		19.4 ab		7.8 abc	†	5.7 a	†
	Forage Radish	24.1 NS		26.3 ab		12.3 ab		10.6 bc		4.9 bc	†	3.4 ab	†
	Winter Rye	21.9 NS		19.7 b		9.3 b		6.6 c		3.0 c	†	2.3 b	†
	Winter Camelina	21.7 NS		19.3 b		7.9 b		13.5 abc		4.0 bc	†	2.3 b	†
	Pennycress	19.6 NS		25.1 ab		6.6 b		17.4 ab		8.4 ab	†	4.0 ab	†
Jun/Jul 2016 Year 2	None: Tilled	16.0 NS	§	51.4 a	‡	27.9 NS		22.9 a	†	22.3 a	†¶	18.0 a	
	Wheat Stubble	11.1 NS	§	50.1 a	‡	22.3 NS		11.7 ab	†	24.0 a	†¶	11.8 b	
	Forage Radish	20.7 NS	§	53.2 a	‡	24.7 NS		11.4 ab	†	16.2 ab	†¶	9.0 bc	
	Winter Rye	13.5 NS	§	50.5 a	‡	26.5 NS		7.2 ab	†	11.0 ab	†¶	8.2 bc	
	Winter Camelina	21.6 NS	§	30.4 a	‡	22.0 NS		3.8 b	†	8.8 ab	†¶	6.2 c	
	Pennycress	38.4 NS	§	41.0 a	‡	28.1 NS		7.0 ab	†	7.1 b	†¶	9.2 bc	
Sept/Oct 2016 Year 2	None: Tilled	17.1 NS		26.8 a	†	6.6 NS		8.4 NS	†	9.0 NS	†¶	4.9 ab	†#
	Wheat Stubble	17.8 NS		17.9 ab	†	6.9 NS		4.6 NS	†	6.7 NS	†¶	4.8 ab	†#
	Forage Radish	19.3 NS		23.1 ab	†	9.1 NS		4.3 NS	†	7.6 NS	†¶	4.0 ab	†#
	Winter Rye	20.5 NS		21.2 ab	†	5.5 NS		4.2 NS	†	5.8 NS	†¶	2.5 b	†#
	Winter Camelina	16.1 NS		18.9 ab	†	11.9 NS		6.7 NS	†	10.1 NS	†¶	7.5 a	†#
	Pennycress	14.3 NS		13.7 b	†	5.5 NS		5.4 NS	†	9.1 NS	†¶	5.3 ab	†#

† indicates a log transformation was performed to meet assumptions of ANOVA

‡ indicates that a boxcox transformation was performed to meet assumptions of ANOVA

§ indicates that a square root transformation was performed to meet assumptions of ANOVA

¶ indicates assumptions of ANOVA were not met

# indicates significance at the P<0.1 level

Figure 1. Yield comparison of soybean from plots with six prior fall planting treatments and of winter camelina and pennycress oilseeds. For each pair of bars, left is 2015, right is 2016. WC=Winter Camelina, PC=Pennycress, RY=Winter Rye, RA=Forage Radish, ST=Stubble, TI=Till.

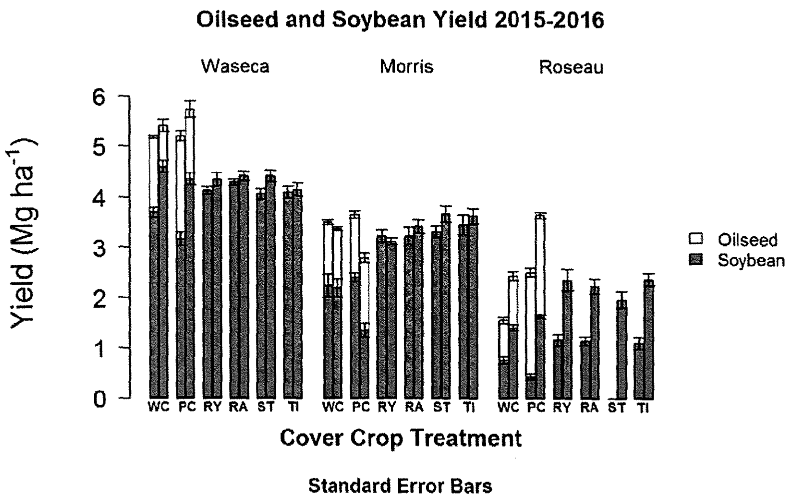
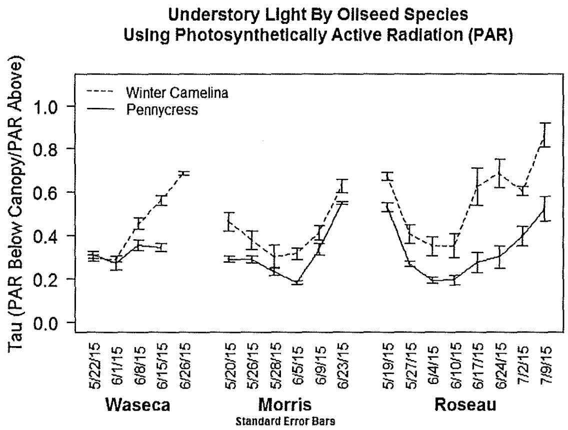


Figure 2. Photosynthetically Active Radiation (PAR) available to soybean under the canopy of winter camelina and pennycress.



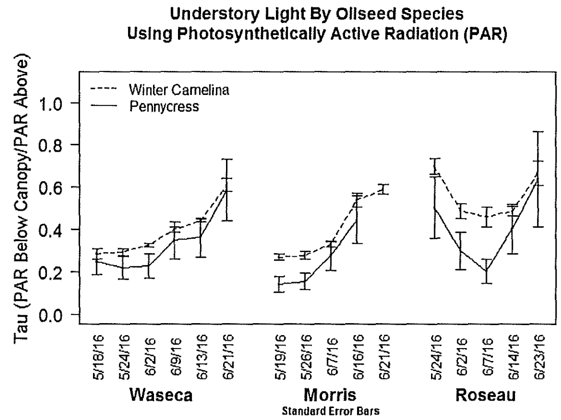
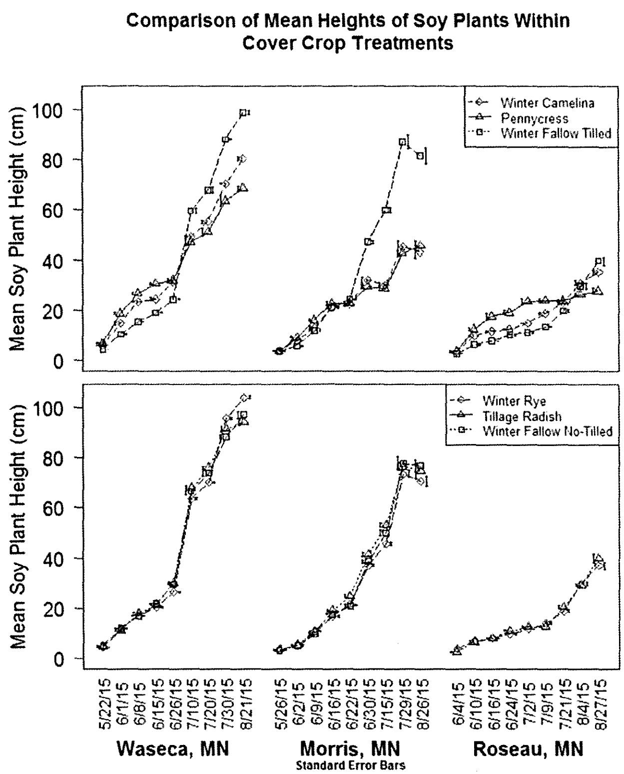


Figure 3. Soybean heights measured in plots under four cover crop treatments and two control treatments.



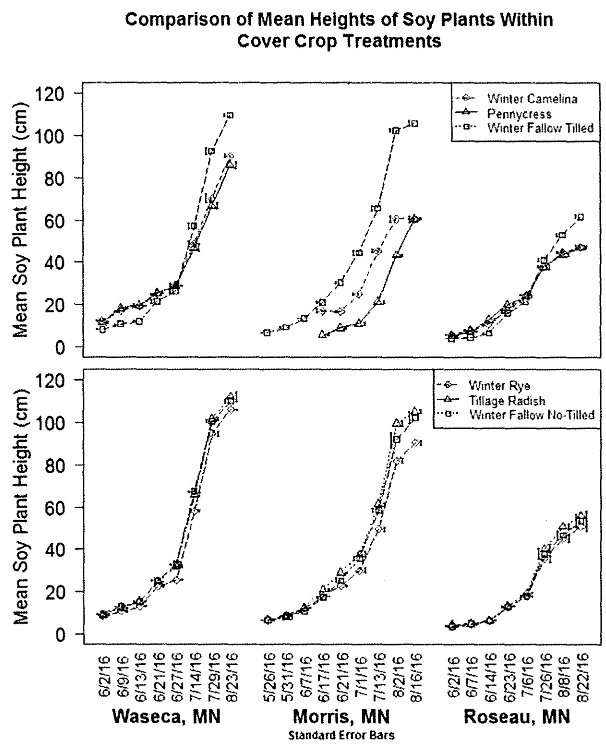
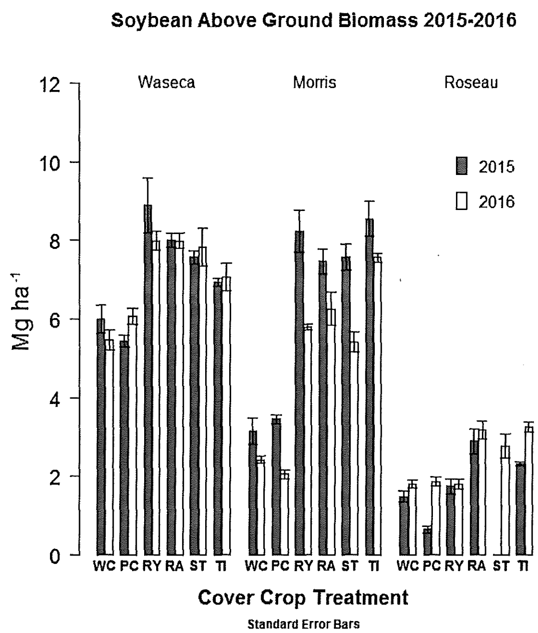
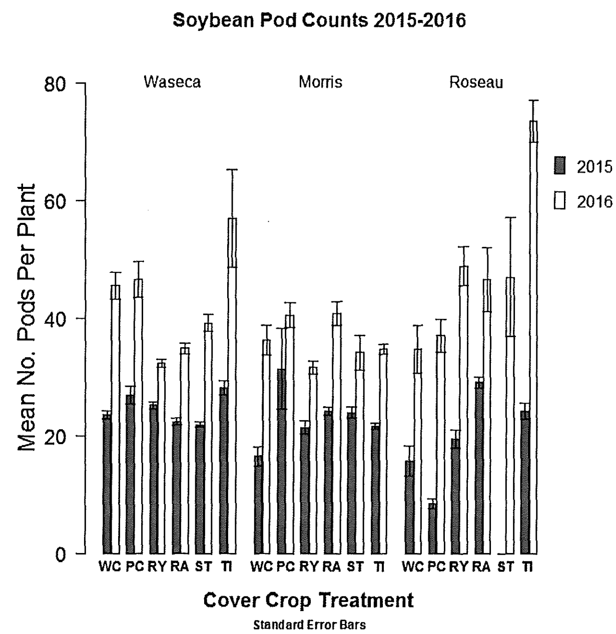


Figure 4. A) Soybean above ground biomass observations from four cover crop treatments and two control treatments. B) The number of pods (per plant) from the biomass samples.





Attachment 2:

DRAFT Manuscript intended for Submission to the Journal of Environmental Quality

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Reduced nutrient leaching and runoff with cash cover crops and soybean in the Upper Midwest

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Keywords

Abstract

Nitrogen and phosphorus contamination of water resources by modern crop production represents not only financial losses to growers, but diminished public support for agriculture as well. Over-winter cover crops may lessen this problem, but adoption of cover crops is limited because they do not provide financial returns to growers in the Upper Midwest. Cash cover crop, such as the winter oilseed, pennycress and winter camelina, can be double-cropped with soybean and increase economic returns to growers. However, their ability to sequester nutrients is unknown. We measured N and P in leachate and runoff in double-cropped winter-camelina/soybean, pennycress/soybean, winter rye/soybean, and radish/soybean and compared these to mono-cropped soybean in traditionally tilled and no-tilled systems. N in leachate was reduced dramatically by all cover crops in autumn, and by pennycress and camelina in spring, which is when most N losses occur. P in leachate was affected little by cover crops. However, pennycress and camelina appreciably reduced suspended solids in runoff, and

likely reduced runoff losses of particulate-bound P. Thus, winter oilseeds may be valuable, cash-generating, and nutrient-sequestering additions to cover crops in the Upper Midwest.

Introduction

Conventional cropping systems in the Upper Midwest typically feature fallow soils from October to June (Ochsner et al. 2010; Sindelar et al. 2015). The exposed soil is subject to erosion from wind and water (Skidmore 1988; O'Neal et al. 2005; Li et al. 2007, 2008a; Li et al. 2008b; Sharratt 2011; Palm et al. 2014) and nutrient leaching into subsurface tile drains or groundwater (Strock et al. 2004; Robertson and Vitousek 2009). Leaching of nitrate into tile lines and groundwater is greatest April through June in Minnesota because few plants are actively growing and precipitation predominates over evapotranspiration at that time (Randall et al. 1997). In addition, 50% of annual drainage occurs by 11 May in this region (Jin and Sands 2003). Both erosion and leaching result in depletion of soil organic matter (Pimentel et al. 1995), reduced soil fertility, and a need for increased inputs of fertilizers. Moreover, erosion and leaching contributes to degradation of water resources (Carpenter et al. 1998). Eutrophication of lakes and rivers is common in Minnesota and the Upper Midwest, leading to classification of many of these water bodies as unsafe (Minnesota Pollution Control Agency 2017).

In areas with intensive agriculture, over-wintering cover crops are an option that can reduce the erosion and contamination of water systems through physical protection of soils and uptake of residual soil nutrients (Dabney et al. 2001; Gesch et al. 2014; Ott et al. 2015). For instance, the presence of actively growing plants, such as perennial forages or conservation reserve plantings (CRP), during April through June nearly eliminated nitrate losses from tile-drained fields in Minnesota (Randall et al. 1997). However, some growers may be reluctant to establish CRP or grow forages for economic and logistical reasons (SARE 2015). Accordingly, other over-winter cropping options are needed to make landscapes in the Upper Midwest green year-round, sequester nutrients, and generate profits for growers. New cover crop options exist to maintain green landscapes during critical periods, and they can provide direct incentive or profit through livestock grazing or seed harvest prior to the start of the normal growing season.

The present study evaluated the use of cover crops in an inter-seeded soybean (*Glycine max* [L.] Merr.) system to mitigate leaching and runoff of N and P from cropping systems. Cover crop treatments included autumn-planted forage radish (*Raphanus sativus* L.), winter rye (*Secale cereale* L.), field pennycress (*Thlaspi arvense* L.), and winter camelina (*Camelina sativa* [L.] Crantz), alongside tilled and stubble (no-till) fallow treatments. All treatments were monitored for nutrient leaching and water runoff. This experimental arrangement allowed us to test the hypothesis that having green cover on the landscape reduces water and nutrient losses compared to the traditional winter-fallowed soil condition.

Methods

Agronomy

This study was conducted from 2014 through 2016 (two complete cropping cycles) on a Barnes loam (fine-loamy, mixed, superactive, frigid Calic Hapludoll) at the USDA-ARS Swan Lake Research Farm, Morris, Minnesota (45.68° N, 95.8° W). Research plots (3.0 x 9.1 m) were arranged on a 2-5% slope in a randomized complete block design including four replicates and two years (Fig. 1). Plots were located in spring wheat stubble that had been sprayed with glyphosate (N-(phosphonomethyl) glycine) at 1.1 kg a.e. ha^{-1} of (glyphosate) about one week prior to planting.

Six treatments were established in the autumns of both 2014 and 2015: chisel plow (15-20 cm deep), wheat stubble (no-till), radish, winter rye, pennycress, and winter camelina. Seeding of radish ('Daikon'), winter rye ('Wheeler'), pennycress ('Beecher Farms'), and winter camelina ('Joelle') cover crops was performed with a no-till drill on August 31, 2014 and September 2, 2015 in 12 rows spaced 25 cm apart.

Seeding rates and depths of the four crops were 11, 76, 7, and 7 kg ha^{-1} and 1.3, 1.3, 0.6, and 0.6 cm, respectively. Chisel plowing (15-20 cm deep) was conducted on the same day as seeding, and the stubble treatment was left undisturbed. Pennycress and camelina treatments were fertilized with N-P-K at 80-30-30 kg ha^{-1} (urea, diammonium phosphate, and potash, respectively) on April 20, 2015 and April 15, 2016). Next, the plowed treatment was disked and harrowed on April 30, 2015 and April 22, 2016, and then all plots were planted with four rows of glyphosate-tolerant soybean (Pioneer P09T74R2) at 445,000 plants ha^{-1}. Soybean row spacing was 76 cm, and rows were inter-seeded between cover crop rows, if present, to minimize potential crop/crop competition. Immediately following soybean planting, winter rye was killed with glyphosate (May 1, 2015; April 22, 2016), but pennycress and winter camelina were allowed to grow. The radish cover crop winter-killed naturally. Seed harvest of pennycress (June 23, 2015; June 16 2016) and camelina (July 2, 2015; June 24 2015) was performed with a plot combine. Subsequently, glyphosate was applied as needed for control of weeds in soybean. Soybean seeds were harvested at maturity in late September or early October with the same plot combine. Seed yield of all crops are reported elsewhere (Ott, 2017).

Cover of standing crop

Normalized difference vegetation index (NDVI) was measured weekly using an active canopy sensor (model ACS-470, Holland Scientific, Lincoln, NE) on all plots following emergence of cover crops in the autumn, ceasing after daily maximum temperatures were < 10 °C. The NDVI measurements resumed following the final frost (-2 °C) in the spring and continued until the harvest of soybeans in early autumn. Measurements were taken by holding the sensor approximately 1 m above the top of the plant canopy on the second row of cover crop or soybean. The same row was sampled each time to document the development of green cover of the plot over time. Measurements within the plot and between replicates were averaged to produce an overall measure of green cover for each treatment.

Water sample collection and analysis

Soil water was sampled using suction cup lysimeters inserted into holes bored into the center of the experimental plots using a hydraulic probe (Fig. 1). To ensure good soil to lysimeter contact, soil from the bottom of the core was mixed with water to form a slurry, which was placed into the bore hole first, followed by insertion of the lysimeters. Each plot in two blocks was outfitted with two SCLs in 2014-2015, one at 30 cm and the other at 60 cm soil depth. Each plot in three blocks was outfitted similarly in 2015-2016, with an additional 100 cm deep lysimeter placed in the no-till, winter rye, pennycress, and camelina treatments. Lysimeters were pressurized to -60 kPa with manual hand pumps after precipitation events ≥ 6 mm. Water, if present, was collected using manual vacuum pumps 24 h later to allow time for water to be drawn into the lysimeter's ceramic cup from the surrounding hemisphere of soil.

Water runoff was measured from plot areas using small, 30 x 150 cm, troughs (Gerlach 1967; Loughran 1989). The troughs were constructed of three steel panels driven partway into the soil at the downslope edge of a plot. Panels were driven 15 cm into the soil and rose 15 cm above the soil surface (Fig. 1). A steel funnel was attached to the downslope end to channel water or soil that flowed over the plot following a precipitation event. At the mouth of the funnel a rubber hose was connected to a 9-L storage tank, which was placed in a small pit.

Runoff troughs were established in 2 replicates of each treatment in both years. Approximately 24 h prior to a forecasted rain event, tanks were cleaned with phosphate-free detergent, triple rinsed with deionized water, then placed in the pits, and attached to the trough assembly. Tanks were monitored for water and soil collection after rainfall or snowmelt events, and replaced with freshly cleaned tanks to collect more runoff if further activity was anticipated.

Water samples from lysimeters and runoff troughs were taken to the laboratory for processing and chemical analysis. The volume of water collected from the runoff troughs was measured to the nearest ml, and a 500 ml subsample was reserved for further analysis. Approximately 50 ml of this subsample was centrifuged at 2500 RPM for 5 min, with the remainder held at 2-5 °C for total suspended solid and particulate P analysis. The supernatant was filtered with a 25 mm acrylic 0.45 μ pore polyethersulfone membrane syringe filter and portioned into two 20-ml subsamples for N and P analyses. Water obtained from lysimeters was filtered and split in the same manner. All N samples were acidified with 2 μl of stock sulfuric acid per 1 ml of filtered sample and held between 2-5 °C until analyzed. P samples were placed in a -10 °C freezer until analyzed.

Nitrate was analyzed using the automated cadmium reduction method, ammonium was analyzed using the automated phenate method (A.P.H.A. 1989), and total nitrogen was measured by combustion (LECO Tru Spec CN analyzer). Soluble reactive phosphorus (SRP) was analyzed using the automated ascorbic acid reduction method (A.P.H.A. 1989) with a flow-injection analyzer (Lachat QuikChem 8500, Hach Co.).

To obtain measures of the total suspended solids (TSS) present in the retained runoff samples, glass fiber filters with 0.45 μ pore size were prepared by triple rinsing with 20 ml aliquots of MilliQ water, dried in a 550 °C muffle furnace for 30 min, tripled rinsed again with 20 ml aliquots of MilliQ water, and finally oven dried at 105 °C for at least 1 h. Individual filters were placed into separate weighing tins, and the weights recorded. Weights of runoff samples were recorded, shaken vigorously, and then approximately 40 ml were filtered through the prepared glass fiber filters. Filters were dried at 105 °C overnight before being reweighed. TSS for each sample was calculated by extrapolation from the subsamples.

The remaining runoff samples were dried at 37 °C until all water was evaporated. Up to 1 g of dried sediment was weighed and the particle-bound phosphorus extracted using 20 ml of sodium bicarbonate

($NaHCO_3$) and 20 min shaking, centrifuged at 2500 RPM for 5 min, the supernatant filtered (0.45 μ), and analyzed using the automated ascorbic acid reduction method. Nutrient loads for nitrate, total nitrogen, SRP, and TSS from the surface runoff collected from the runoff troughs were calculated for each sample as concentration times volume collected.

Statistical methods

Nutrient data from the lysimeters were separated into three biologically relevant periods: (1) autumn cover crop growth (emergence of cover crops to first hard freeze of -2°C), (2) spring cover crop growth (April to oilseed harvest), and (3) post oilseed harvest (pennycress and camelina harvest to soybean harvest). The non-parametric Kruskal-Wallis test was used to identify significant differences among treatments for concentrations of nitrate, total N, and SRP gathered from lysimeters. Pairwise comparisons were conducted using the Dunn test with Bonferroni correction if significant differences were found from the Kruskal-Wallis test. Mean separation letters were assigned to treatments to distinguish similar and dissimilar groups using web-based software (Dallal 2000). All statistical tests for nutrients in lysimeters were conducted in R (R Core Team 2015).

Runoff events were evaluated as a binary dataset (runoff or no runoff after rainfall) with a general linear mixed model (PROC GLIMMIX, SAS9.4) to determine if the number of runoff events within seasons each year differed significantly across treatments. A repeated measures test (PROC GLIMMIX) was used to determine if runoff volume (L $event^{-1}$) were influenced by treatment, season, and year. For this test all zero values were eliminated. Both tests confirmed the number of events and the volume o and nutrient concentrations of events differed by biological period ($P < 0.05$), but did not differ by treatment. Therefore the total volume of runoff (L yr^{-1}) and total nutrient loads (g yr^{-1}) were evaluated with a mixed model for the two years of the study. All GLIMMIX procedures used the log-normal distribution, block replicates were treated as random factors, and year was tested separately as a random and a treatment effect. Statistical tests were parameterized to minimize Akaike information criterion (AIC) or Generalized Chi Square divided by the degrees of freedom. Multiple comparison tests were performed using the PDIFF or SLICEDIFF functions to evaluate differences within a season at $p < 0.1$.

Results

Rainfall patterns

Differences in the pattern of rainfall occurred between the two years of the study. Autumn (September through November) precipitation for 2014 and 2015 (and 20-year average) was 39 and 117 mm (172 ± 30 mm). Rain fell on 17 days during autumn in both years, with the daily maximum rainfall being 12 mm in 2014 and 34 mm in 2015.

Spring (April through June) rainfall for 2015 was 241 mm and 148 mm in 2016 (209 ± 17 mm). During spring 2015 there were 27 rainfall events, with the daily maximum being 50 mm. In 2016 comparable numbers were 31 events and 22 mm.

Rainfall during the post-harvest period (July through August) was 177 and 278 mm (156 ± 15 mm) for the same years. Number rainy days and maximum rainfall events were 16 and 39 mm for 2015, and 20 events and 54 mm for 2016.

Thus, both autumn seasons were dry, springs were average to dry, and summers were average to wet. Both years experienced days with intense storms.

Green Cover

NDVI for each season showed similar patterns between years, notably in the spring and post-oilseed harvest periods (Fig. 2). After autumn establishment, radish and winter rye quickly increased in green cover compared to camelina and pennycress, but by early October all cover crop treatments exceeded index values of 0.50 in 2014 and 0.25 in 2015. Volunteer wheat was responsible for NDVI values in the stubble and tilled treatments.

For the spring period, stubble, tilled, and radish treatments all remained at baseline until approximately 30 days after soybeans were seeded. Green cover in winter rye plots increased until rye was sprayed with herbicide at soybean inter-seeding, and cover quickly declined before increasing because of soybean emergence and growth about 30 days later in 2015 and 45 days later in 2016. NDVI measurements for both pennycress and camelina increased at the start of spring, topping at an index value of 0.7 before declining as the crops matured. Immediately following harvest, the pennycress and camelina plots increased in green cover again because of soybeans whose growth previously was inhibited under the oilseed crop canopy.

Soil Water Nutrients

For the 2014 autumn period too little rain fell to saturate soil. In autumn 2015, average nitrate and total N concentrations in leachate in pennycress and winter camelina treatments did not differ from other treatments at any depth (Fig. 3). Radish and winter rye had the lowest nitrate and total N concentrations at both the 30 and 60 cm depths. Which corresponded with the high NDVI values for these crops during that same time period. No significant differences among treatments at 100 cm for nitrate or total nitrogen were found, and there were no significant differences in SRP among treatments at any depth.

For the spring growing periods of 2015 and 2016, average nitrate and total N concentrations in leachate at 30 and 60 cm from pennycress and camelina treatments were significantly lower than in tilled and stubble treatments (Fig. 4). At 100 cm, no differences were observed for nitrate, but total N in pennycress and camelina treatments was significantly lower than the stubble treatment. No significant differences of SRP were detected at any depth or treatment. Because most leaching of nutrients occurs during the April-June period in the Upper Midwest (Randall et al. 1997, Heggenstaller et al. 2008, Kladivko et al. 2014), the nutrient-scavenging potentials of camelina and pennycress at this time may be important.

Following the harvest of the winter oilseeds but prior to soybean harvest, average nitrate and total N concentrations in leachate from 30 and 60 cm depths were higher in the oilseed treatments compared to the radish and winter rye treatments (Fig. 6). At 100 cm, average nitrate and total N concentrations in pennycress and winter camelina were higher than those in winter rye. In winter camelina these values also were lower than for the stubble treatment. Average SRP concentrations were higher in the oilseed treatments than in the tilled treatment at 30 cm, whereas at 60 cm only pennycress exceeded the tilled treatment. At 100 cm, leachate concentrations of SRP did not differ among treatments. Although differences in nutrient concentrations existed among treatments during summer (July and August), the probability of leaching to groundwater is very low during this time of year.

Water and Nutrient Runoff

Total volume of water runoff showed a trend ($P = 0.07$) among treatments in each season across study years (Fig. 6). In the autumn through spring thaw interval, pennycress had significantly less total runoff compared to winter rye, but it was similar to all other treatments. In contrast, camelina did not differ from any treatment. Radish had less runoff than winter rye and till treatments, perhaps because of root channels for which the plant is well known (Chen and Weil 2010). In the spring growth period camelina had significantly less runoff compared to the till treatment, but was similar to all other treatments, whereas pennycress did not differ from other treatments. In the post-harvest period, pennycress and camelina had significantly less runoff compared to the radish treatment, but were similar to all other treatments. No significant differences were found in nitrate, total N, total suspended solids, or particulate P across treatments (Fig. 6 and 7). In relation to rainfall patterns, seasonal differences also were observed in ammonium, nitrate, total N, and SRP concentrations, as well as between year differences for ammonium and total N (data not shown).

Discussion

Year-round green cover reduced nutrient concentrations in soil leachate. This was most clear during the spring season with treatments containing the winter annual cover crops winter rye, pennycress, and camelina, compared to plots that were winter-fallowed, including those with radish, which was winter-killed. Traditional winter-fallowed systems had nitrate concentrations in leachate of 20 to 55 mg L^{-1} during spring, whereas analogous concentrations in winter rye, pennycress, and camelina treatments were typically < 10 mg L^{-1}. In the Upper Midwest, spring is a critical time for loss of N from agricultural systems due to snow melt followed by heavy precipitation and low evapotranspiration demand; it is also the season when most nitrate enters groundwater or is lost through tile drainage (Randall et al. 1997, Kladivko et al. 2014).

Soybeans also sequestered nutrients once they entered the V6-R1 stage, as evidenced by nutrient concentrations in leachate and/or runoff during the post-oilseed harvest period. In treatments that included inter-seeded soybean with pennycress and camelina, there was some degree of continuous green cover over nearly the entire year (i.e., autumn of year 1 to autumn of year 2). Following the harvest of winter oilseeds, soybean cover was lower than in other treatments (Fig. 2; post-harvest period), and tended to have greater nutrient concentrations in leachate compared to the till, stubble, winter rye, and radish treatments in which soybean was well-established. This nutrient-enhanced leachate was most likely related to the lower amount of soybean cover coupled with relatively high precipitation during the July to August period. Relay-cropping soybean into standing camelina can reduce soybean biomass and yield, but the total grain produced by both crops exceeds that of conventionally grown soybean and can provide economic incentive for adoption of a double-cropping system (Gesch et al. 2014, Berti et al. 2015). Whatever the case, N-enriched leachate from the pennycress and camelina treatments still was much lower (< 20 mg L^{-1}) than what was found in the fallow (i.e., till and stubble) systems during autumn and spring periods.

Cover crops actively scavenge residual soil nitrate, but uptake residual N depends on climate, soil nitrate levels, planting time, and cover crop species (Gallaher 1977; Delgado et al. 1999; Dabney et al. 2001). In autumn, radish and winter rye treatments were most efficient at scavenging residual N and reducing N enrichment of leachate at both the 30 and 60 cm soil depths compared with pennycress and camelina cover crops. Radish, which does not survive winter in Minnesota, and winter rye are robust plants in autumn whereas pennycress and camelina remain small and in the rosette stage until spring. Accordingly, NDVI green cover measurements were greater in autumn for radish and winter rye, indicating greater biomass than the oilseeds. In the spring, however, residual N was scavenged more effectively by pennycress, camelina, and winter rye, and N in leachate was reduced by these treatments. NDVI data indicated greater green cover and active growth of these oilseed crops. Despite termination of winter rye in April of both years, having a growing cover, even for a short duration, reduced nitrate enrichment of leachate. Additionally, the radish and stubble treatments did not have growing green cover in the spring prior to soybean planting, yet N in leachate still was reduced somewhat compared to the tillage treatment. This reduction is likely due to the incomplete decomposition of the radish and stubble plant materials by spring and, hence, continued immobilization of nutrients (Kuo et al. 1996; Justes et al. 1999; Kuo and Jellum 2002).

While nitrate has been implicated in causing surface water eutrophication, in many parts of the USA excessive P can be more detrimental (Schindler, 1977; USEPA 1990; Carpenter et al. 1998), causing extensive growth of aquatic plants. When these plants die, oxygen in the water is depleted during decomposition, which poses problems for fisheries, recreation, and drinking water (Landsberg 2002; Wolf et al. 2017).

Agriculture is one of the major sources of excess P in surface waters (Sharpley et al. 1994). P is often bound to soil particles, organic matter, or found in insoluble form (Brady and Weil 2002). However, P in drainage waters is primarily in soluble form (Sharpley and Smith 1991; Gu et al. 2017). Differences in SRP concentrations in leachate were only evident during the post-harvest time period, at which time pennycress and camelina had greater concentrations than the till and radish treatments at 30 and 60 cm, respectively. Fertilizer P was applied in April to the pennycress and camelina treatments. Although the amount was small, it may have contributed to the higher leachate P concentrations in these latter treatments (Sharpley 1981, Sharpley et al. 1994).

Cover crops can reduce runoff and sediment transport as well as increase water infiltration (Dabney et al. 1999, 2001), but whether cover crops provided similar benefits in our experiments is unclear, though some trends were apparent. For runoff volumes and associated nutrient concentrations, there was no clear detectable effect from the presence of green covers. Runoff results indicated strong seasonal differences and differences between years, likely due to variation in rainfall patterns among seasons and between the two years. Although winter cover crops like pennycress and camelina tended to have lower runoff volumes than traditionally fallowed treatments in spring and summer, differences were not always significant. Additionally, the radish treatment had the least amount of runoff, likely due to the macropores created by the large taproots of these plants. In contrast, the winter rye treatment had the greatest runoff in the fall and during thaw events, possibly due to greater amounts of plant materials that captured and retained snow in the plots.

The winter cover crops, pennycress and camelina, planted in a relay system with soybean likely reduced the leaching of soil N, and to a limited extent, reduced total water runoff compared to conventionally tilled or other winter fallow scenarios. The benefits for improved water quality attributed to pennycress and camelina add to their versatility as crops in the Upper Midwest, as they can produce harvestable oilseeds (Zubr 1997; Gesch and Archer 2013) as well as provide abundant early-season floral resources for beneficial insects such as bees (Eberle et al. 2015; Thom et al. 2017). Consequently, this combination of economic viability and environmental benefits_provides an important opportunity to increase cropping diversity, expand beneficial insect habitat, and improve impaired water systems in or near agricultural lands. Incorporating pennycress and camelina production into current agricultural practices is not without pitfalls, but the multitude of benefits that these crops provide may help to alleviate unintended effects of intensive agricultural production. Careful management of agricultural land to produce increased amounts of food and fuel in an efficient manner is a global priority, one that needs to be solved through innovative and integrated strategies, and the planting of the winter cover crops like pennycress and camelina may be such an approach.

Acknowledgements

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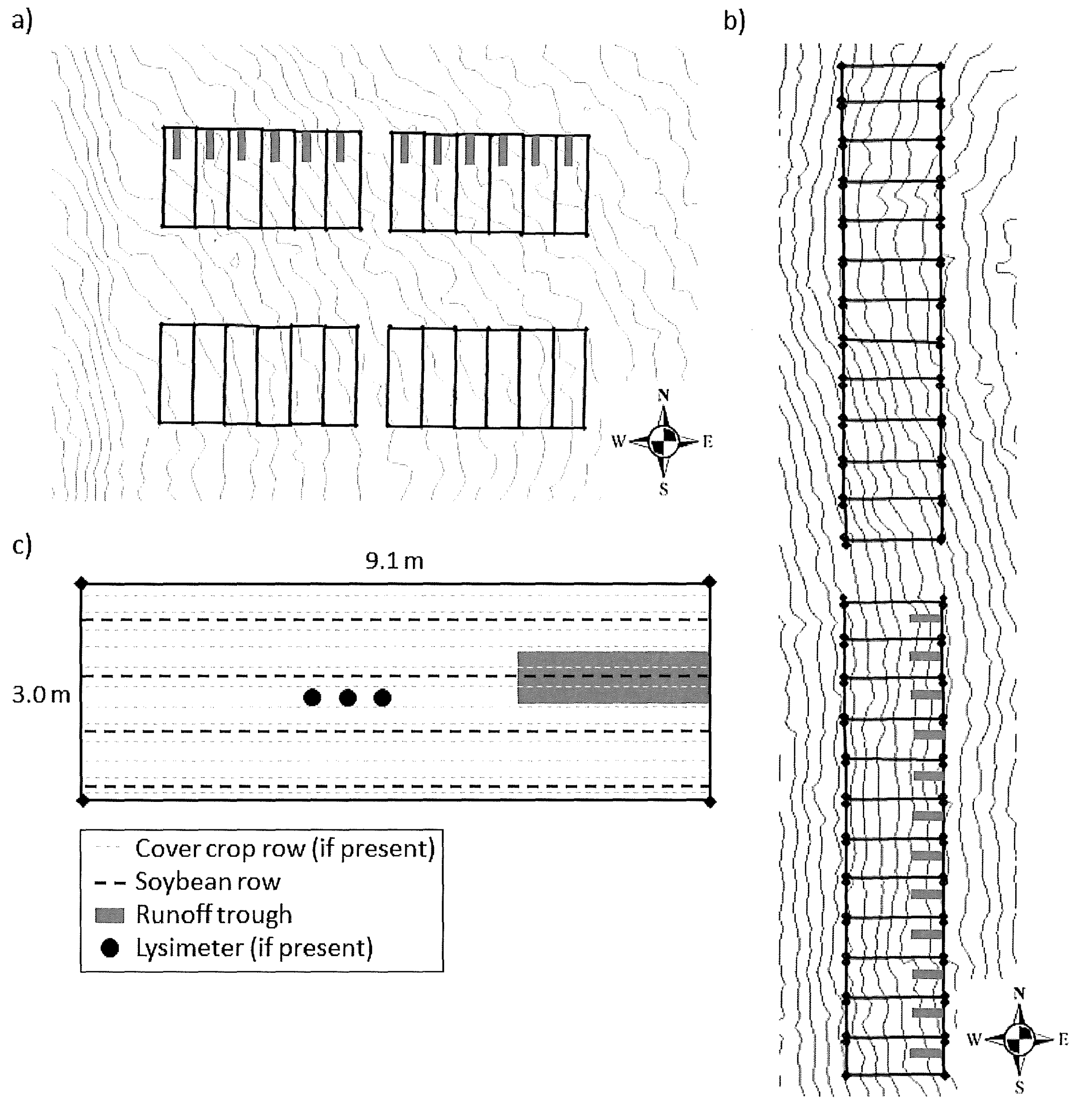

Figure 1. Experimental plots at the Swan Lake Research Farm, Morris, MN. Treatment arrangement and 10 cm topographic contour lines in a) 2014-2015 and b) 2015-2016; c) Placement of planted crop rows and water sampling equipment

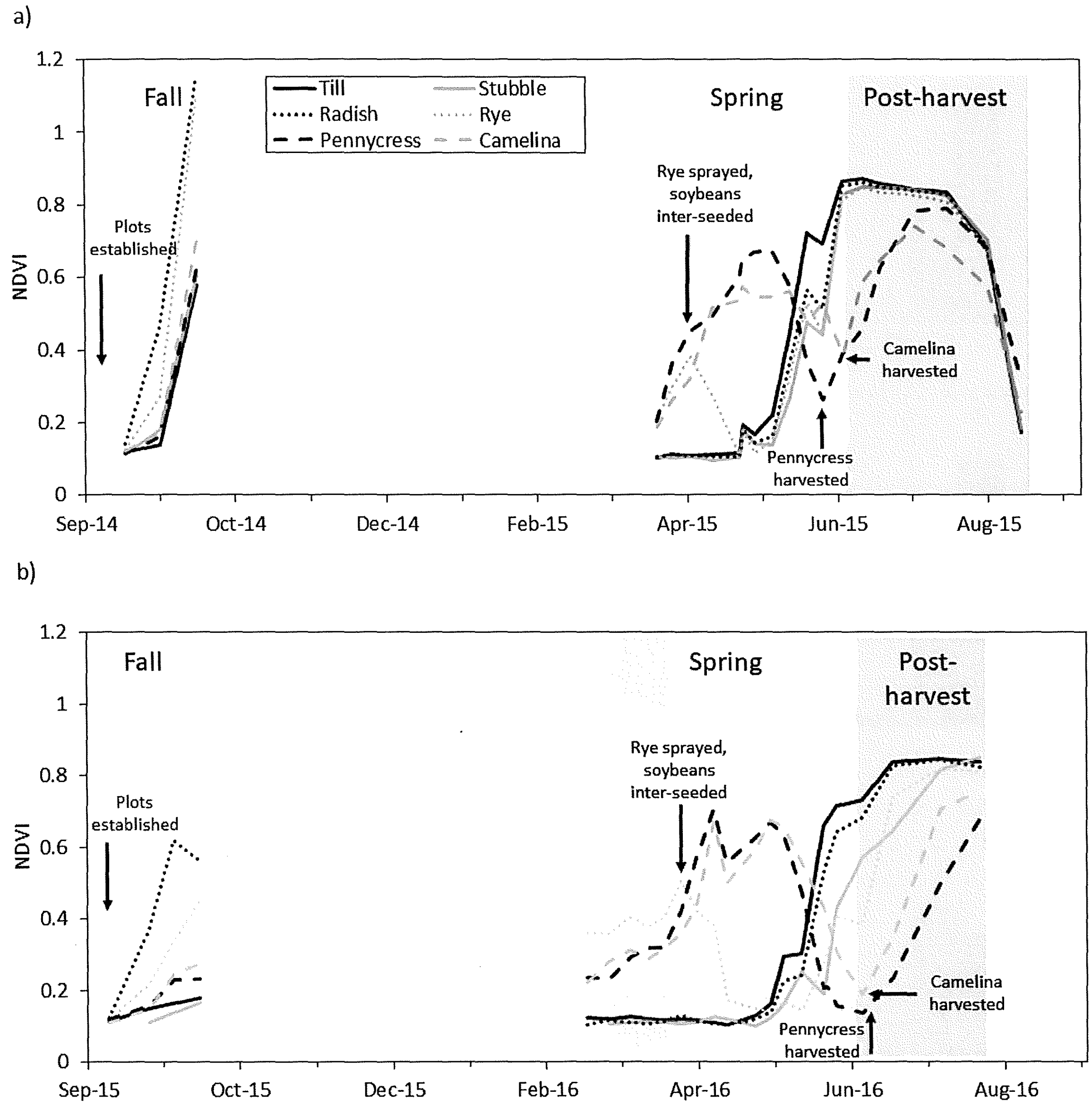

Figure 2. Normalized difference vegetation index (NDVI) of experimental plots at the Swan Lake Research Farm, Morris, MN. a) 2014-2015; b) 2015-2016

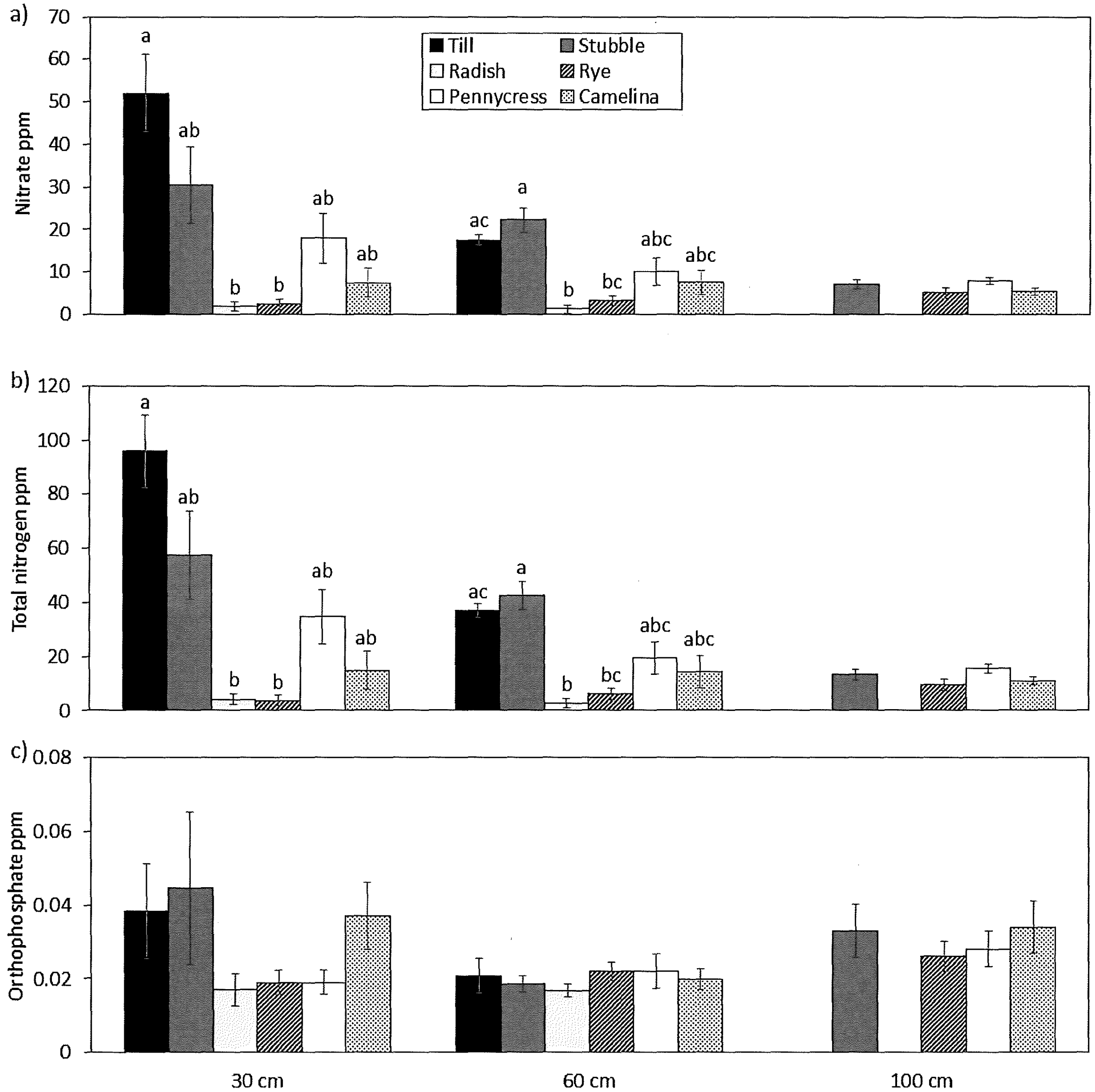

Figure 3. Average nutrient concentrations of water samples collected in autumn (September-November) from suction-cup lysimeters installed in experimental plots at the Swan Lake Research Farm, Morris, MN. The 100 cm lysimeters were installed only in stubble, winter rye, pennycress, and camelina and only in 2015-2016. Columns are means (± SE). Letters represent differences based on the Dunn test. Absence of letters atop bars indicates no significant differences among treatments.

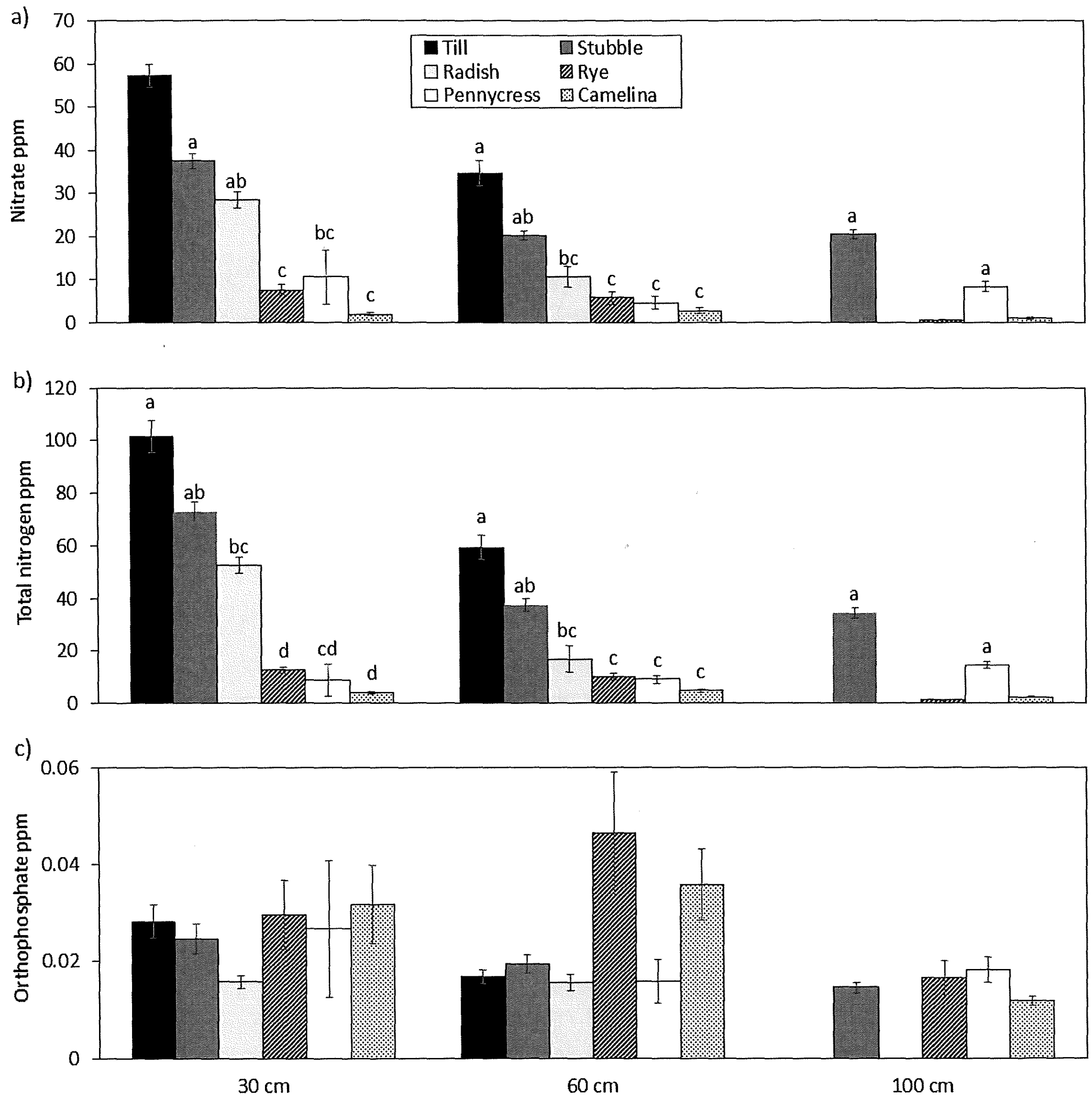

Figure 4. Average nutrient concentrations of water samples collected in spring (April through June) from suction-cup lysimeters installed in experimental plots at the Swan Lake Research Farm, Morris, MN. The 100 cm lysimeters were installed only in stubble, winter rye, pennycress, and camelina and only in 2015-2016. Columns are means (± SE). Letters represent differences based on the Dunn test. Absence of letters atop bars indicates no significant differences among treatments.

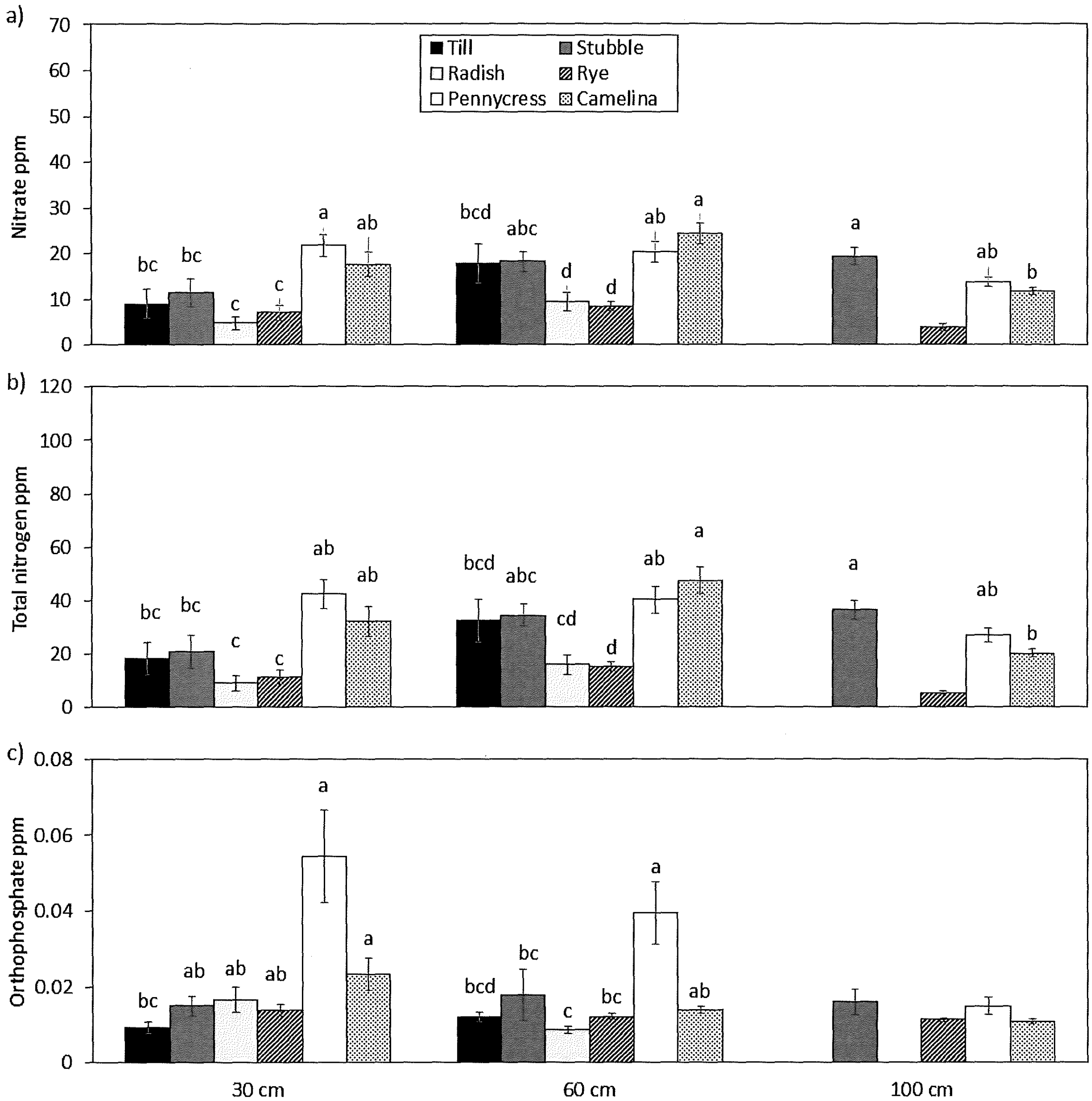

Figure 5. Average nutrient concentrations of water samples collected in autumn (July-August) from suction-cup lysimeters installed in experimental plots at the Swan Lake Research Farm, Morris, MN. The 100 cm lysimeters were installed only in stubble, winter rye, pennycress, and camelina and only in 2015-2016. Columns are means (± SE). Letters represent differences based on the Dunn test. Absence of letters atop bars indicates no significant differences among treatments.

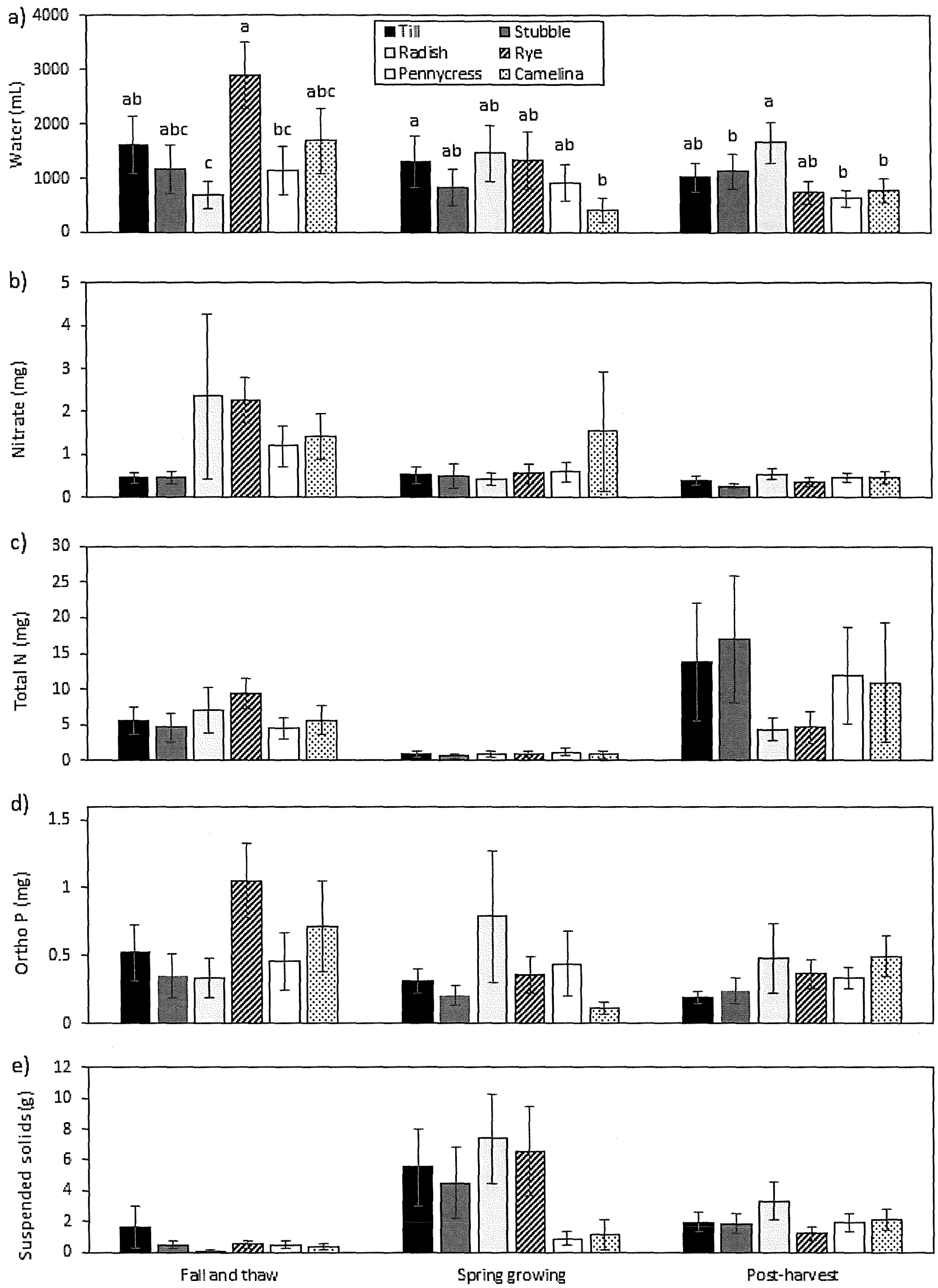

Figure 6. Average runoff volumes and nutrient concentrations collected from runoff troughs installed in experimental plots at the Swan Lake Research Farm, Morris, MN, during three seasons: September through March (fall and thaw), April through June (spring growing), and July-August (post-harvest of oilseeds). Columns are pooled means (± SE).

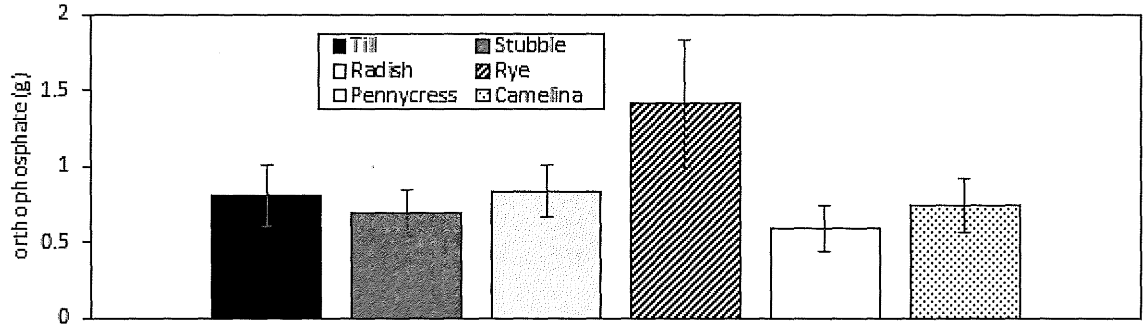

Figure 7. Particulate phosphate from water runoff collected from runoff troughs installed in experimental plots at the Swan Lake Research Farm, Morris, MN, from September 2014 through August 2015 and September 2015 through August 2016. Columns are pooled means (± SE) for all seasons and years.

Winter Camelina Growers Guide for Minnesota

(Double-Cropping with Soybean)

Agronomy Group

Forever Green Initiative

University of Minnesota – USDA-ARS

The Agronomy Group is comprised of the following individuals listed in alphabetical order by surname: Jim Anderson, Kevin Anderson, John Baker, Roger Becker, Rebecca Carlson, Senyu Chen, Frank Forcella, Katheryn Frels, Axel Garcia, Russ Gesch, Cody Hoerning, Gregg Johnson, Dave Marks, Matthew Ott, M. Scott Wells, and Don Wyse.

Overview

Winter camelina is a mustard-type plant closely related to canola that produces high concentrations of oil in its seeds. The seeds can be sown in autumn, they germinate and emerge relatively quickly after sowing given adequate soil moisture. Seedlings typically produce "rosettes" before the deepfreeze arrives in November. Rosettes are circular bundles of seedling leaves that may be 1" to 6" in diameter by late autumn. However, even with very late plantings, say mid-October, with seedlings only in the cotyledon stage of growth by early November, the young camelina plants still survive Minnesota winters.

As the snow melts in March or April, the rosettes resume growth. Typically they produce more leaves, and by mid to late April they begin "bolting." Bolting refers to the initiation of flower stalks. Pale yellow flowers usually are visible in late April or early May. The flowers are self-fertile (they pollinate themselves), but many insect pollinators, including honey bees, also will visit the flowers for nectar and pollen, and these visits facilitate cross-pollination of the flowers.

Small pear-shaped fruits develop from the flowers. The fruits technically are called silicles, which are basically capsules, and each capsule contains about a dozen small seeds. The capsules tend to be mature and are ready to harvest before the end of June. At that time the plants are about 30" tall, with most of the seed capsules in the upper half of the plant. Combining is relatively simple, and standard machinery typically is used to harvest the crop's small seeds directly. Swathing is not necessary.

Oil from seeds of winter camelina has high levels of alpha-linolenic acid or ALA. This is one of the omega-3 fatty acids that are held in high regard by nutritionists because these fatty acids promote heart health. Most cooking oils do not contain ALA or other omega-3 fatty acids because of their propensity to oxidize. Fatty acid oxidation means rapid rancidity and short shelf lives for cooking oils. Fortunately, camelina oil also contains a natural anti-oxidant called tocopherol. Tocopherol confers a very long shelf life for camelina oil, unlike any other oil with a high ALA content. This combination of traits (natural flavor, nutritional benefits, and long shelf life) means that winter camelina has good market potential.

Variety selection

Five winter-hardy varieties have been tested in Minnesota and in some surrounding states. These are 'Bison', 'BSX-WG1', 'Joelle', 'WG1-35', and 'WG4-1'. The vast majority of research in Minnesota has been performed with 'Joelle'. It has superior cold and freezing tolerance. In the approximately 10 years of research on this variety in Minnesota, it has never failed to survive the winter. Winter camelina is, however, susceptible to extended periods of water-logging. When sown in depressions that collect water in spring, death of rosettes has been noted.

Curiously, when these same varieties have been sown in the Great Plains of western Kansas and eastern Wyoming, winterkill has been a significant issue, with survival in only one of three years. Ironically, winter temperatures in these areas are much higher than those in Minnesota; thus, the ultimate cause of winterkill is not clear.

The University of Minnesota has initiated a breeding program for winter camelina to hasten flowering time, decrease seed shattering, and increase seed yield. Consequently, new and productive varieties with equally high cold tolerance to 'Joelle' are expected in the future for Minnesota. In the meantime, however, our recommendation for Minnesota growers is to plant 'Joelle'.

Field Selection

Winter camelina is drought-hardy and grows well on many soil types. However, it does not tolerate water-logging, so clay soils and fields with poor drainage should be avoided.

Winter camelina also is highly sensitive to some persistent herbicides, such as the triazines, sulfonylureas, and imidazolinones. If atrazine was applied in spring in a preceding corn crop, the herbicide would not have had enough time to deactivate by September when the winter camelina is sown. Winter camelina is especially sensitive to residues of sulfonylurea herbicides, as well as to those of the imidazolinones. Toxic levels of residues of these herbicides can remain in soil for more than two years.

Do not plant winter camelina in fields where in the two previous crop years the field might have received any one of the following herbicides.

Corn	Potato	Small grains	Soybean	Sugar beet
Aatrex	Matrix	Ally	Classic	Upbeet
Accent		Amber	Harmony	
Basis		Express	Pursuit	
Beacon		Maverick	Python	
Matrix		Peak	Raptor	
Option			Scepter	
Permit			Valor	
Python				
Valor				

The trade names of the above herbicides are associated with the following common chemical names: Aatrex (atrazine), Accent (nicosulfuron), Ally (metsulfuron), Amber (triasulfuron), Basis (thifensulfuron), Beacon (primisulfuron), Classic (chlorimuron), Express (tribenuron), Harmony (thifensulfuron), Matrix (rimsulfuron), Maverick (sulfosulfuron), Option (foramsulfuron), Peak (prosulfuron), Permit (halosulfuron), Pursuit (imazethapyr), Python (flumetsulam), Raptor (imazamox), Scepter (imazaquin), Upbeet (triflusulfuron), and Valor (flumioxazin)

The table at right gives trade names of herbicides whose residues may affect winter camelina. These are herbicides labeled for use in crops planted in Minnesota. Many of these herbicides have multiple trade names that are not listed in the table. Thus, pay attention to the common chemical names on herbicide labels. The common chemical names associated with trade names are listed in the table's footnote.

Planting time and seedbed preparation

In Minnesota successful plantings occurred anytime from early September to mid-October. Seed yields and oil concentrations of seeds tend to be higher with late September and early October plantings. Most research plots were sown into stubble of spring wheat. This was done initially to insure overwinter survival by trapping an insulating layer of snow amongst the six-inch tall wheat stems. However, winter survival was equally high even in years without much snowpack. Moreover, autumn growth of seedlings is greater in the absence of residues from previous crops, and survival is equally good. In brief, winter camelina can be sown with or without residues from previous crops.

Recent research has emphasized broadcasting (with a specialized "Hi-Boy" seeder) winter camelina seeds into corn crops at tasseling and up to the R6 stage of corn development. Seedling establishment was quite high, but during the following spring the high levels of corn residue severely depressed growth and development of camelina. However, if the corn residue was baled and removed, and only 12" stalks remained in autumn, camelina seedling growth was vigorous in spring. Drill-seeding can also be used for successful establishment of camelina after removing corn for silage.

Accordingly, our recommendations are that winter camelina seeds be sown in late September in tilled and harrowed soil or no-tilled into residues of crops such as wheat, soybean, dry bean, sunflower, silage corn, etc. If sown into growing (tassel-stage and beyond) field corn, then corn stalks must be baled after corn grain harvest and removed leaving not more than 12" tall stubble.

Seeding depth

Winter camelina has very small seeds, each about 1 mm wide and 2 mm long. About 400,000 to 500,000 seeds weigh one pound. Such small seeds require shallow planting. Best results occur with a planting depth of 0.5", but seedlings still can emerge with a planting depth as deep as 1.5" as the seeds are quite vigorous for their size.

As mentioned above, broadcasting also can lead to good establishment, but only if the germinating seeds are protected from desiccation by living crops or crop residues. High crop residue levels must be lowered before resumption of camelina rosette growth in spring. If seeds are broadcasted onto bare soil, a harrow or roller-packer should follow to insure good soil-seed contact.

Our recommendation, however, is to drill camelina seeds at 0.5" deep in soil and gently use the drill's press wheels to pack soil above the seed rows.

Seeding rate and row spacing

Winter camelina seeds typically have germination rates greater than 65%. Although a target density of about 15 plants per square foot is desired, plants in sparse populations branch readily. Consequently, thin stands and low seeding rates still can produce high yields. Indeed, stands of only 4 plants/sq ft sometimes can yield as much or more than those at the target density. However, research has shown that higher densities near the targeted amount do an excellent job of suppressing fall and early summer weeds. Therefore, a seeding rate of 5 to 6 lbs/A of seeds typically is recommended for drill-seeding, while for broadcast seeding, a higher rate of 10 lbs/A is recommended to assure sufficient stands.

Row-spacings between 6" and 12" can be successful. However, higher seed yields tend to occur with the narrower spacings of 6", 8", or 10". Our recommendations are to use a seeding rate of 5 to 6 lbs/A and drill the seeds in rows spaced at 6". However, if winter camelina is going to be double-cropped with soybean, then every fifth row should be a "skip-row," and this empty row will be drilled to soybean the following spring (see section on "Drilling soybean," below).

Weed control

Autumn sowings of winter camelina typically do not require pre-plant herbicide applications. However, special situations easily can be imagined where treatments may be necessary. For example, when no-till drilling into wheat stubble, if numerous wheat volunteers are present, then preplant glyphosate (e.g., Roundup), glufosinate (e.g., Liberty), or some other burndown herbicide should be applied. Otherwise, tillage may beneficial.

Although the need is unlikely, if high densities of summer-growing grassy and broadleaf weeds are expected to be a problem after autumn sowing of winter camelina, the herbicides listed in the adjacent table safely can be applied preplant incorporated (PPI, shallowly incorporated in the soil) or preemergence (PRE; applied to the soil surface before the crop and weeds emerge).

Trade name	**Common name**	**Product rate**	**Application time**
Command	clomazone	3 oz/A	PRE
Dual Magnum	s-metolachlor	1.3 pt/A	PRE
Outlook	dimethenamid	17 oz/A	PRE
Prowl	pendimethalin	1.5 pt/A	PPI or PRE
Quinclorac	quinclorac	1.5 pt/A	PRE
Sonalan	ethalfluralin	2 pt/A	PPI
Treflan	trifluralin	1.5 pt/A	PPI
Zidua	pyroxasulfone	2.5 oz/A	PRE

If camelina seeds already germinated and camelina seedlings are intermixed amongst wheat volunteers, then a grass herbicide such as quizalofop (e.g., Assure at 5 oz/A) or sethoxydim (e.g., Poast at 1 pt/A), plus crop oil concentrate or surfactant, should be used to control volunteer wheat, as well as quackgrass or other grassy weeds, such as foxtails. Camelina seedlings are tiny and do not compete well with other plants.

Once camelina seedlings are well established by mid to late October, they form a carpet of rosettes that is quite competitive with weeds, not only in autumn, but also the following spring when summer-growing weeds begin to emerge. However, some weeds, like dandelion, which likely germinated the previous autumn, can thrive in camelina stands in spring. Postemergence applications of bromoxynil (Buctril at 1 pt/A) and fluroxypyr (Starane at 0.4 pt/A) in spring can suppress dandelion selectively in winter camelina, as well as provide good control of several other broadleaf weeds. No other POST herbicides are known to be tolerated by winter camelina.

Because winter camelina is such a new crop in Minnesota, none of the herbicides listed above are labeled yet for use in the state on this crop. Special-use permits from the Minnesota Department of Agriculture will be required for use of these herbicides in commercial plantings of winter camelina.

Fertility

One of the values of growing winter camelina is that it sequesters excess soil nitrate in the autumn, thereby preventing water-borne movement of this nutrient into groundwater or surface water. However, if the soil has little nitrate in early autumn, growth of camelina seedlings may be diminished. For highest seed yields camelina requires approximately 80 lb/A of total N (i.e., residual soil N plus fertilizer N) in the top 2 feet of soil. Thus, fertilizer rates applied to winter camelina are about 50 lb/A of N and 25 lb/A each of P and K if seed yields of 1000 lb/A are expected. The requirement for sulfur is not well-established for winter camelina, as it is for some other oilseed crops, and many reports suggest extra sulfur is unnecessary.

The best times to apply fertilizers are not yet settled. Winter camelina seedlings grow fast and more luxuriantly when fertilizers are applied at or near the time of seeding, but doing so lessens the benefits of using winter camelina to sequester residual nitrates in soil and from soil water in autumn. In Minnesota we have had good results with delaying broadcast fertilizer application until after snowmelt in late March or early April when the soil has begun to thaw. However, studies of split autumn/spring applications compared with spring-only applications have not been performed, but they are underway. Studies comparing the effects on plants and the environment of broadcasting versus incorporating fertilizers also have not been conducted yet.

Drilling soybean (and other crops) into camelina

Camelina is an economically viable crop in Minnesota only if it is double-cropped with soybean or some other summer-growing crop. Soybean can be no-till drilled into the skip-rows of camelina (see photo) when the camelina is beginning to bolt. ("Bolting is the initiation of fast-growing flower stalks.) Bolting typically occurs in late April to early May in west central Minnesota and mid to late April in southern Minnesota. By planting the soybean seeds in the skip-rows, the intensity of competition between soybean and rapidly growing camelina is diminished. A full-season soybean can be chosen for such a double-crop system, which is known as "relay-cropping."

Alternatively, drilling soybean can be delayed until after camelina harvest in late June. However, a very short-season soybean variety will be needed in such a sequential double-crop system. This type of double-crop system is called "sequential cropping."

In either relay or sequential systems, soybean should be drilled at a standard rate (180,000 to 200,000 seeds/A) and depth (1" to 2").

A wide variety of summer crops other than soybean also can be sown as relay or sequential crops with camelina. This has been demonstrated successfully for both sunflower and proso millet. Borage, buckwheat, calendula, cuphea, dry bean, sweet corn, and teff currently are being investigated.

Combine harvesting

Camelina seeds should be harvested when 80-90% of pods are mature, that is yellow to grayish-brown in color, when seeds rattle when capsules are shaken, and when mature seeds have a reddish brown color. The dates for this operation vary, but tend to be in late June. Although the seed capsules stay intact for weeks, severe wind and rainstorms during this time can lead to high seed shattering losses. Seed moisture at harvest typically is less than 20%. Post-harvest drying is required until seed moisture decreases to 8% to 9%.

Standard combines can be used to harvest winter camelina seeds despite the small size of the seeds.

If the camelina is being double-cropped with soybean, the cutting bar of the combine needs to be set at about 6" to 8" or the height of the soybean.

Additional adjustments to combine settings may be needed. For instance, the reel speed must be low to prevent shattering of camelina seed capsules, cylinder speed should be medium, sieves and concaves set tightly, fan speed should be medium, and a small to medium screen is recommended.

Seed storage

Because seeds are so small, care must be taken to prevent losses by sealing openings in grain carts and beds of trucks. Seeds must be dried to 8% to 9% seed moisture to maintain seed quality.

Ecosystem services

Winter camelina flowers earlier (late April) than other crops, and even earlier than most spring-flowering wild plants. Consequently, its flowers are prized by many native pollinators as well as honey bees. Transient honey bees typically are returning to Minnesota from the Gulf and West Coasts in April, and camelina flowers provide abundant and natural pollen and nectar for them.

Both hover flies and bumble bees are native