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Field Pennycress Production and Weed Control in a Double Crop System with Soybean in Minnesota

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ABSTRACT

Sustainable intensification of agricultural systems has been suggested as a way to increase food, fiber, energy, and feed to meet future demands. Field pennycress (*Thlaspi arvense* L.) is proposed as a means for temporal intensification of agriculture, increasing profitability through oilseed production while providing needed cover to address soil and water quality issues. Field research was conducted across four environments in Minnesota to (i) evaluate pennycress planting date and seeding rate on pennycress and soybean [*Glycine max* (L.) Merr.] seed production and (ii) determine the role of pennycress systems as a weed management tool. Pennycress seeding rate had a direct effect on pennycress yield at Rosemount but not at Waseca or Lamberton locations. The use of a companion cover crop along with pennycress further reduced pennycress seed yield at Rosemount, but not Waseca or Lamberton suggesting that water availability is a key driver in pennycress productivity. The effect of pennycress and cover crops on soybean yield was also dependent on location. At Rosemount, soybean yield was reduced when pennycress was planted ahead of soybeans both years of the study while there was no effect of pennycress on soybean yield at Waseca. Although soybean yield was reduced at Rosemount, the combined pennycress and soybean seed yield was greater. This research shows the potential for a double cropping system of pennycress–soybean to increase overall seed yield and reduce early-season weed pressure.

Sustainable intensification of agricultural systems has been suggested as a way to increase food, fiber, energy, and feed to meet future demands. Heaton et al. (2013) describe the concept of temporal intensification in agriculture whereby the goal is to increase the number of crops grown in a given time period. The goal is to capture as much of the growing season as possible to gain economic benefits beyond a single crop. This strategy can be extended beyond Heaton et al. (2013) to include multiple economic, environmental, and ecological values that can be realized from planting two or more crops across the entire year. This is especially relevant in the upper Midwest where large portions of the agricultural landscape are devoid of cover from early fall through late spring (Ochsner et al., 2010). During this period, a lack of plant vegetative cover leaves the soil vulnerable to erosion, therefore leading to reduced soil quality and off-site movement of nutrients and other material. Surface and subsurface loss of nitrate N is also compounded by a lack of vegetative cover leading to poor water quality in rivers and lakes (Randall et al., 2003; Snapp et al., 2005). Many growers consider establishing cover crops, such as winter rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth), clovers, and forage radish (*Raphanus sativus* L. var. *longipinnatus*), to provide living plant cover to mitigate the effects of leaving the soil bare. However, cover crops are not perceived as directly contributing to the profitability of the cropping system (Leavitt et al., 2011).

Field pennycress is as a crop that fits within a temporal intensification concept resulting in greater profitability while providing needed cover to address critical soil and water quality issues. Field pennycress is a winter annual that can be harvested for seed in late May to early June–early enough to plant a full season soybean that can be grown on the same land area. Pennycress is a member of the Brassicaceae family and is a native to Eurasia but has become naturalized throughout North America (Sedbrook et al., 2014). Being a winter annual, pennycress overwinters as a rosette (Warwick et al., 2002) and can grow in a variety of habitats (e.g., wet moist valleys or dry exposed knolls) (Best and McIntyre, 1975). Pennycress is self-compatible and readily autogamous, with an outcrossing rate estimated at 10–20% (Best and McIntyre, 1975). Pennycress is also a prolific seed producer with a single plant producing from 13,162 to 14,914 seeds (Hume, 1990).

Although field pennycress is considered by many to be a weed, it is currently being evaluated as an important source of oil for biofuel production (Moser et al., 2009; Phippen and Phippen, 2012). Hojilla- Evangelista et al. (2013) showed that pennycress is easily converted to biodiesel. Additionally, Boateng et al. (2010) showed that fast pyrolysis of defatted seed meal can also produce stable high-C, low-oxygen high-energy liquid fuel intermediates that can be formulated into jet fuels. Field pennycress seed meal has also been specifically tested as a biofumigant (Vaughn et al., 2006), allowing growers to enter other non-traditional markets.

From a production standpoint, pennycress may be seeded anytime in the fall, for example, into standing corn or immediately after corn harvest. Forage radish or winter rye is often planted with

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pennycress to enhance soil cover in the fall and winter. Although rye provides a large amount of soil cover in the fall, it must be terminated in the spring to prevent competition with the grain crop. Forage radish is another winter annual cover crop that emerges quickly and grows rapidly in the fall. However, forage radish typically winter-kills in northern climates. With both rye and forage radish covers, there is little information regarding any competitive effects that these covers may have with pennycress. Regardless, pennycress growth is resumed in early spring, producing seed that can be harvested early enough to allow for a second crop of soybean to be planted. The seed can then sold to processors as a potentially high-value oil seed crop (Johnson et al., 2007; Phippen and Phippen, 2012). The idea of obtaining both pennycress and soybean crop in the same season can have significant economic benefits, provided that yield is maintained in both crops.

There are agronomic benefits that may be realized by integration of pennycress into corn or soybean systems. Pennycress has the potential to provide late fall and early spring weed suppression. Cover crops can reduce early weed growth by competing with weeds for limited resources, for example, light, nutrients, and water (Clark et al., 2007; Kruidhof et al., 2008, 2009). Early canopy development in pennycress can reduce light quality and light quantity resulting in changes in the morphology of weeds (Gramig and Stoltenberg, 2009). Furthermore, pennycress is in the Brassicaceae family, which is known to produce the allelopathic compounds, primarily glucosinolates (Vaughn et al., 2006). These compounds can affect the germination and growth of weeds, and may be a source of early season weed control.

Pennycress may also promote populations of beneficial insects, especially pollinators and crop pest predators. Nearly a third of the nation's honeybee (*Apis mellifera*) colonies reside in Minnesota, North Dakota, and South Dakota, yet honeybees are limited in this region by the low abundance and diversity of food sources in early spring, a contributing factor to "colony collapse disorder" (Spivak et al., 2011). Pennycress begins flowering in April and early May when honeybee colonies are returning to the upper Midwest, thus, pennycress can serve as a food source for honeybees and native pollinators in early spring. In addition, pennycress may also provide overwintering habitat for predatory insects, increasing potential for biocontrol of pests.

Farming strategies focused on crop diversification will ultimately maintain flexibility in crop production decisions and increase market power. Therefore, strategies that allow for "temporal intensification" of agriculture are in the interest of both farmers and industrial processors. Crop diversification also provides many environmental benefits such as soil and water quality through integration of winter annual or perennial on the landscape (Snapp et al., 2005). Pennycress can offer all of these advantages and has a tremendous opportunity for genetic improvement (Dorn et al., 2013). The objectives of this research were to (i) evaluate pennycress planting date and seeding rate on pennycress and soybean seed production and (ii) determine the role of pennycress systems as a weed management tool.

MATERIALS AND METHODS

Field experiments were conducted at one site in 2011 and three sites in 2012. In 2011, experiments were conducted at the University of Minnesota Rosemount Research and Outreach Center in Rosemount Minnesota (44°43′24″ N, 93°06′23″ W). In 2012, experiments were conducted at the Rosemount Research and Outreach Center, the Southern Research and Outreach Center in Waseca, MN (44°04′22″ N, 93°31′21″ W), and the Southwest Research and Outreach Center in Lamberton, MN (44°14′19″ N, 95°18′50″ W). Soils at the Rosemount site were a well-drained Waukegan silt loam (fine-silty or sandy-skeletal over sandy, mixed, superactive, mesic Typic Hapludoll) with pH of 6.9 and organic matter content of 3.8%. Soils at the Waseca site were a Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) with a pH of 6.1 and organic matter content of 5.6% while soils at the Lamberton site were a moderately well drained Normania clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) with a pH of 5.7 and organic matter content of 4.5%. All field locations tested high for soil P and K.

Experiment 1. Pennycress, Soybean, and Total Seed Crop Yield as Influenced by Companion Cover Crop and Pennycress Seeding Rate

In 2011, the experimental design was a randomized complete block in a split-plot arrangement with three replicates. Main plots were planted to either an oat (*Avena sativa* L.) or a forage radish (cultivar Groundhog) cover crop with a no cover treatment as a control. Subplots comprised pennycress seeding rates (0, 5.5, or 11.0 kg ha^{-1}). Oat used in this study consisted of a commercially available blend of high-yielding, medium maturity varieties. The experimental site was disked and cultipacked on 6 Sept. 2010. Pennycress along with oat and radish cover crops was planted with a drill on 25-cm rows on 8 Sept. 2010. The oat and radish cover crops were planted at 66 and 11 kg ha^{-1} rates, respectively. Pennycress plant stand and height was measured on 24 May 2011 in three 0.08 cm^2 quadrats and averaged across each plot. Pennycress seed yield was measured by hand harvesting a square meter area of each plot on 29 May 2011. Glyphosate [N-(phosphonomethyl) glycine] was applied as a burn-down treatment to the entire study area at a rate of 0.84 kg a.e. ha^{-1} before planting soybean. Soybean (Pioneer 91Y72) was planted on 11 June 2011 at a rate of 296,000 seeds ha^{-1}. Soybean crops were machine harvested on 13 October. Subplot size was 4.5 by 6.1 m.

In 2012, a third treatment was added to explore the added effect of soybean row spacing on seed crop yield and weed control. The experimental design was a randomized complete block in a split-split plot arrangement with three replications at all locations. Main plots were soybean row spacing (38 and 76 cm) and subplots were planted to either an oat or forage radish cover crop with a no cover crop treatment as a control. Sub-subplots were pennycress seeding rate (0, 5.5, or 11.0 kg ha^{-1}). Sub-subplot size was 3 by 6.1 m at all locations. Oat used in this study consisted of a commercially available blend of high-yielding, medium maturity varieties. The experimental site was disked and cultipacked on 6 Sept. 2010. Pennycress, oat, and radish were planted with a drill on 25-cm rows on 25 Aug. 2011 in Rosemount, 23 Aug. 2011 in Waseca, and 30 Aug. 2011 in Lamberton. Cover crops for the 2012 experiment were planted with a drill on 25-cm rows at the same 2010 seeding rates. Pennycress plant stand and height was measured on 24 May 2011 in three 0.08 cm^2 quadrats and averaged across each plot. Pennycress seed was harvested in square meter area of each plot on 29 May, 30 May, and 6 June

Table 1. Pennycress seed yield as influenced by companion cover crop and pennycress seeding rate for Exp. 1 at Rosemount.

Cover crop	Pennycress seed yield		
	Pennycress seeding rate, kg ha^{-1}		
	0	5.5	11.0
	kg ha^{-1}		
2011			
PC†	0e‡	1340a	1086b
PC+radish	0e	970bc	1013b
PC+oat	0e	723d	823cd
2012			
PC	0e	1187b	1387a
PC+radish	0e	604c	477d
PC+oat	0e	587cd	666c

† PC, pennycress.

‡ Means within each year followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

at Rosemount, Waseca, and Lamberton, respectively. The entire study area received a burn down application of glyphosate at a rate of 0.84 kg a.e. ha^{-1} before planting soybeans in spring 2012. Soybean (Pioneer 90M80) was planted at Rosemount on 14 June at a rate of 296,000 seeds ha^{-1}. At Waseca, soybean (P91Y72) were planted on 8 June while soybean (P91Y72) was planted at Lamberton on 11 June 2012. Soybean crops were harvested on 24, 15, and 17 October, at Rosemount, Waseca, and Lamberton, respectively. Average monthly precipitation and air temperature is shown in Table 1.

Weed cover was assessed by visually estimating percent cover in each plot 24 May 2011 using a visual scale of 0 to 100 with 0 = no weeds and 100 = complete coverage. In 2012, weed biomass was harvested from a 1 by 0.5 m^2 quadrant placed perpendicular to the rows in each plot on 26 May at Rosemount, 27 May at Waseca, and 2 June at Lamberton. Within each quadrant weeds were cut at the soil surface and placed in brown paper bags. All biomass samples were dried at 60°C in a forced-air oven for 3 d and weighed to determine aboveground plant biomass on a dry matter basis (Davis et al., 2005).

Experiment 2. Pennycress, Soybean, and Total Seed Crop Yield as Influenced by Companion Cover, Pennycress Variety, and Pennycress Planting Date

In 2011, the experimental design was a randomized complete block in a split-split plot arrangement with three replicates. Main plots were pennycress seeding date (fall vs. spring seeding) with subplots planted to either oat or forage radish (cultivar Groundhog) cover crop with a no cover crop treatment as a control. Sub-subplots comprised pennycress seeding rates (0 , 5.5, or 11.0 kg ha^{-1}). Oats used in this study consisted of a commercially available blend of high-yielding, medium maturity varieties. The experimental site was disked and cultipacked on 6 Sept. 2010. Pennycress was planted with a drill on 25-cm rows on 8 Nov. 2010 and 8 Apr. 2011. Cover crops were planted with a drill on 25-cm rows on 8 Sept. 2010 at a rate of 66 and 11 kg ha^{-1} rates for oat and radish, respectively. Pennycress plant stand and height was measured on 24 May 2011 in three 0.08 cm^2 quadrats and averaged across each plot. Pennycress seed was hand harvested in a square meter on 29 May 2011. Glyphosate was applied as a burn-down treatment to the entire study area at a rate of 0.84 kg a.e. ha^{-1} before planting soybeans. Soybean (Pioneer 91Y72) was planted on 11 June at a rate of 296,000 seeds ha^{-1}. Soybean crops were harvested on 13 October. Subplot size was 4.5 by 6.1 m.

In 2012, the experimental design was a randomized complete block in a split-split plot arrangement with three replications at all locations. Main plots were pennycress seeding date (August or September) with subplots comprising two cultivars of pennycress (MN106 and MN111–an accession from New York). Sub-subplots were planted to either oat or forage radish (cultivar Groundhog) cover crop with a no cover crop treatment added as a control. Oat used in this study consisted of a commercially available blend of high-yielding, medium maturity varieties. The experimental site was disked and cultipacked on 22, 26, and 26 Aug. 2011 at Rosemount, Waseca, and Lamberton, respectively. Pennycress was planted with a drill on 25-cm rows at a rate of 11 kg ha^{-1} on 23 Aug. 2011 and 21 Sept. 2011 at Rosemount and on 30 Aug. 2011 at Lamberton. The late planting date was not established due to extraordinarily dry soil conditions. Cover crops were planted with a drill on 25-cm rows on 23 and 30 Aug. 2011 at Rosemount and Lamberton, respectively, at a rate of 66 and 11 kg ha^{-1} rates for oat and radish, respectively. Subplot size was 3 by 6.1 m at Lamberton and 3 by 9.1 m at Rosemount. Pennycress plant stand and height was measured on 27 May, 27 May, and 2 June 2012 at Rosemount, Waseca, and Lamberton, respectively in three 0.08 cm^2 quadrats and averaged across each plot. Pennycress seed yield was measured by hand harvesting a square meter area of each plot on 29 May and 6 June at Rosemount and Lamberton. The entire study area received a burn-down application of glyphosate at each site at a rate of 0.84 kg a.e. ha^{-1} before planting soybean on 13 July, 29 June, and 28 June at Rosemount, Waseca, and Lamberton, respectively. At Rosemount, soybean (Pioneer 90M80) was planted on 14 June at 296,000 seeds ha^{-1} and machine harvested 24 October. Soybean (Pioneer 91Y72) was planted at Lamberton and Waseca and machine harvested on 17 and 15 October, respectively.

Weed cover was assessed by visually estimating percent cover in each plot 24 May 2011 using a visual scale of 0 to 100 with 0 = no weeds and 100 = complete coverage. In 2012, weed biomass was harvested from a 1 by 0.5 m^2 quadrant placed perpendicular to the rows in each plot on 26 May at Rosemount, 27 May at Waseca, and 2 June at Lamberton. Within each quadrant weeds were cut at the soil surface and placed in brown paper bags. All biomass samples were dried at 60°C in a forced-air oven for 3 d and weighed to determine aboveground plant biomass on a dry matter basis (Davis et al., 2005).

Analysis of variance was conducted using the mixed model procedure (PROC MIXED) in SAS (version 9.3, SAS Institute, Cary, NC). In 2011, cover crop treatments and pennycress seeding rate were treated as fixed effects. Replications and all interaction terms with replicates were treated as random effects. In 2012, soybean row spacing, cover crop treatments, and pennycress seeding rate were treated as fixed effects. Replications and all interactions terms with replications were treated as random effects. All data was analyzed by site and year. The lack of homogeneous variance associated with weed cover data in 2011 was corrected using an arcsine-square root transformation before analysis. Means were separated using a Fisher's protected least significant difference (LSD) at 10% significance level.

RESULTS

Precipitation

In 2010, precipitation from August to November (period of pennycress and cover crop seeding and establishment) was 12 cm above normal at Rosemount (Fig. 1). In 2011 and 2012, precipitation was 19 and 5.2 cm below normal, respectively, during the growing season (April–November), respectively. However, precipitation was above normal during the first half of the growing season (April–July) and below normal during the last half of the growing season (August– November) in 2011 and 2012. Consequently, pennycress and cover crops were seeded into very dry soil in fall 2011 resulting in poor establishment and growth. At Waseca, precipitation was 27.1 cm below normal from August to November 2011 and 25 cm below normal during the growing season in 2012. Precipitation at Lamberton was 22.8 cm below normal from August to November 2011 and 8 cm below normal during the 2012 growing season. Precipitation tended to be below normal during most of the 2012 growing season at Lamberton with the exception of an isolated rain event in May that increased the season average precipitation. In general, Waseca tended to be drier in 2011 and 2012 followed by Lamberton and Rosemount.

Experiment 1. Pennycress, Soybean, and Total Seed Crop Yield as Influenced by Pennycress Seeding Rate and Companion Cover Crop

Rosemount 2011

Pennycress seed yield was greater at the 5.5 kg ha^{-1} seeding rate compared the 11.0 kg ha^{-1} seeding rate when planted without a companion cover crop (Table 1). However, planting pennycress with oat or radish reduced pennycress seed yield at the lower seeding rate whereas only oat reduced pennycress seed yield at the higher seeding rate when compared to planting pennycress alone. Pennycress plants were 19 to 27 cm shorter at maturity in treatments that included a companion cover crop compared to pennycress alone. A companion cover crop did not influence pennycress stand density ($P = 0.31$). Soybean seed

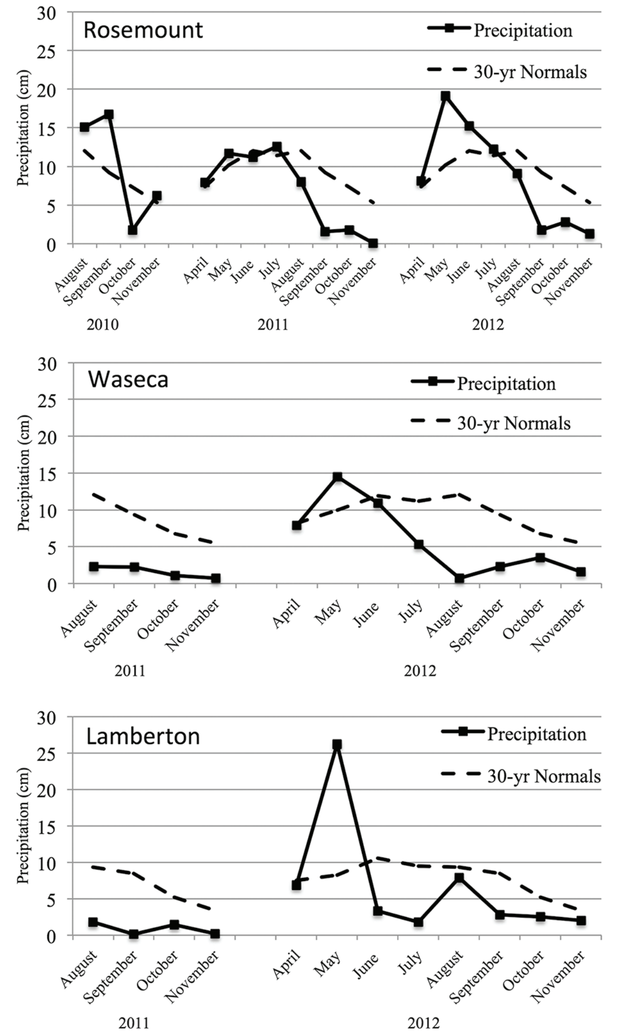

Fig. 1. Monthly total precipitation at the Rosemount experimental site during fall 2010 along with the 30-yr average (1971–2000) and monthly total precipitation at the Rosemount, Waseca, and Lamberton experimental sites during the growing season 2011–2012 and the 3-yr average (1981–2010).

Table 2. Effect of soybean row spacing, cover crop, and pennycress seeding rate on pennycress seed yield for Exp. 1 at Rosemount, Waseca, and Lamberton in 2012.

	Field pennycress seed yield				Soybean seed yield				Total seed yield			
	Rosemount		Waseca	Lamberton	Rosemount		Waseca	Lamberton	Rosemount		Waseca	Lamberton
Treatment	2011	2012	2012	2012	2011	2012	2012	2012	2011	2012	2012	2012
	kg ha^{-1}											
Soybean row width												
38 cm	–	558a†	460a	108a	–	2639a	2882a	nr	–	3197a	3343a	nr
76 cm	–	532a	449a	111a	–	2448a	2406a		–	2980a	2855b	
Cover crop												
PC‡	nr§	nr	513a	113a	1962a	271a	2660a	1977.7a	2771a	nr	3173a	2091a
PC+Radish			462a	112a	1988a	2377b	2672a	2075.6a	2649a		3134a	2187a
PC+Oat			390a	104a	1785a	2536ab	2600a	1898.1a	2261a		299a	2002a
Pennycress planting rate												
0 kg ha^{-1}	nr	nr	0b	0b	2194a	3114a	2568a	nr	2194b	nr	2568b	nr
5.5 kg ha^{-1}			672a	161a	1798b	2241b	2569a		2809a		3240a	
11.0 kg ha^{-1}			694a	168a	1743b	2275b	2796a		2678a		3490a	

† Means in the same column and main effect followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

‡ PC = Pennycress.

§ nr = Not reported. Statistically significant interaction was noted. Therefore, main effect means are not reported.

yield was reduced by 18 to 20% in a pennycress/soybean double crop system compared to soybean alone (Table 2). Conversely, total seed crop yield was 18 to 22% greater in a pennycress/soybean double crop system compared to soybean alone. Although using a companion cover crop reduced overall pennycress seed yield, there was no affect on soybean seed or total seed crop yield.

Rosemount 2012

Pennycress stand following establishment in fall 2011 was 8.2 to 20.8 plants 30 cm^{-1} of row with the greatest pennycress stand occurring at the higher seeding rate without a companion cover crop. However, below normal precipitation from August to November 2011 resulted in limited pennycress growth during this period (pennycress height less than 2 cm). In 2012, pennycress stand density at maturity was 11.7 to 20.0 plants 30 cm^{-1} of row (similar to 2011) with the greatest pennycress stand occurring at the higher seeding rate without a companion cover crop ($P = 0.002$). Pennycress height at maturity was 29 to 34 cm shorter when using a radish cover crop and 20 to 24 cm shorter when using an oat cover crop compared to pennycress alone ($P = 0.001$). Pennycress seed yield in the absence of a companion cover was similar to 2011 (Table 1). However, pennycress seed yield in 2012 was greater when planted at the higher compared to the lower seeding rate in the absence of a companion cover crop. Pennycress yield was reduced 50% when planted with a cover crop regardless of pennycress seeding rate and tended to be lower than pennycress yield in 2011.

Soybean yield was reduced when pennycress was used in a double crop system with soybean compared to soybean alone regardless of pennycress seeding rate, similar to 2011 results (Table 2). Soybean yield was also reduced when a radish cover was used the previous fall compared to no cover crop. There was no reduction in soybean yield when oat was used as a cover crop. Although soybean yield was reduced in a double crop system with pennycress, total seed yield was greater in the double crop system compared to soybean alone. Total seed yield followed the same trends as pennycress seed yield whereby total seed yield was greater when pennycress was seeded at the higher rate compared to the lower rate without a companion cover crop. Furthermore, using a companion cover crop with pennycress reduced total seed yield, especially when using a radish cover crop. Soybean row spacing had no effect on soybean or total seed yield at Rosemount in 2012.

Waseca 2012

Pennycress stand following establishment in fall 2011 was 10 to 21.7 plants 30 cm^{-1} of row with the greatest pennycress stand occurring at the higher seeding rate without a companion cover crop. Similar to the Rosemount location, pennycress growth in fall 2011 was limited (pennycress height less than 2 cm) due to below normal precipitation. In 2012, pennycress stands were 8.3 to 14.3 plants 30 cm^{-1} of row at harvest with the greatest pennycress stand occurring at the higher seeding rate without a companion cover crop ($P = 0.09$). Pennycress height at harvest averaged 79 cm and was not influenced by seeding rate or cover crop ($P = 0.17$). Pennycress seed yield and soybean seed yield was not affected by pennycress seeding rate, companion cover crop, or soybean row spacing (Table 2). However, total seed yield was 22 to 28% greater when pennycress and soybean were used in a double crop system compared to soybean alone. At Waseca, using a cover crop had no effect on total seed yield. Although row spacing did not influence soybean and pennycress seed yield, total seed yield was greater in the 38 cm compared to the 76-cm soybean row spacing treatments.

Table 3. Soybean seed yield and total seed crop yield as influenced by cover crop and pennycress seeding rate for Exp. 1 at Lamberton in 2012.

Soybean row spacing	Pennycress seeding rate, kg ha^{-1}		
	0	5.5	11.0
	kg ha^{-1}		
		Soybean seed yield	
38 cm	2447a†	2135b	2347ab
76 cm	1386d	1830c	1756c
		Total seed yield	
38 cm	2447a†	2283a	2523a
76 cm	1386d	2003b	1917b

† Means followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

Lamberton 2012

Pennycress stand following establishment in fall 2011 was 12 to 15 plants 30 cm^{-1} of row with the greatest pennycress stand occurring at the higher seeding rate without a companion cover crop. Pennycress growth was poor in the fall of 2011 (pennycress height less than 1 cm), similar to the other locations. In 2012, pennycress stands at maturity were 7.2 to 10.0 plants 30 cm^{-1} of row with the greatest stand density occurring at the higher seeding rate of pennycress without a companion cover ($P = 0.0001$). Pennycress height at maturity averaged 39 cm and was not influenced by pennycress seeding rate or companion cover crop ($P = 0.68$). Pennycress seed yield was not influenced by pennycress seeding rate or companion cover crop, similar to the Waseca site (Table 2). However, pennycress yield in general tended to be lower than at other locations.

Soybean seed yield was not influenced by cover crop in 2012. However, soybean yield was greater in narrow compared to wide row soybean regardless of the presence or absence of pennycress (Table 3). Within narrow row soybean, there was no difference in soybean yield between the higher seeding rate of pennycress and soybean alone. When soybean was planted in wide row spacing, soybean yield was greater when pennycress was part of a double crop system compared to soybean alone, regardless of pennycress seeding rate. Total seed crop yield was greater in narrow compared to wide row soybean (Table 3). Within narrow row soybean systems, the presence of pennycress did not increase or decrease total seed yield compared to soybean alone. In wide row soybeans, pennycress in a double crop system with soybean increased total seed yield compared to soybean alone. Total seed crop yield was not affected by a cover crop at Lamberton in 2012.

Experiment 2. Pennycress, Soybean, and Total Seed Crop Yield as Influenced by Pennycress Seeding Date and Rate, Companion Cover Crop, and Pennycress Variety

Rosemount 2011

Pennycress stands were 18 to 40 plants 30 cm^{-1} of row at harvest with the greatest pennycress stand occurring at the higher seeding rate ($P = 0.0001$). Pennycress height at maturity was 40 to 46 cm with the tallest plants occurring in plots that

Table 4. Pennycress seed yield as influenced by pennycress planting date and cover crop and seeding rate in Exp. 2 at Rosemount in 2011.

Treatment	Pennycress planting date	
	November 2010	March 2011
	Pennycress seed yield	
	kg ha^{-1}	
Cover crop		
None	154abc†	155ab
Radish	128cd	133bcd
Oat	116d	163a
Pennycress planting rate		
0	0c	0c
5.5	195b	182b
11	204b	270a

† Means within the same main effect followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

were planted in March at the higher seeding rate ($P = 0.09$). Pennycress seeding rate did not influence pennycress yield when planted in November 2010 (Table 4). However, pennycress yield was greater at the 11 kg ha^{-1} seeding rate when planted in March 2011 (270 kg ha^{-1}) compared to November 2010 (204.4 kg ha^{-1}) while there was no difference in seed yield between planting dates at the 5.5 kg ha^{-1} seeding rate. When averaged over pennycress seeding rates, an oat companion crop reduced pennycress seed yield when planted in the fall (Table 4). When planted in the spring, there was no difference in pennycress seed yield with or without a companion cover crop. However, a radish cover crop reduced pennycress seed yield compared to an oat cover crop. These results are not surprising considering that both radish and oat covers are not present in the spring. Increased competition from the oat cover crop in the fall 2010 reduced yield whereas the oat cover crop was not present in the spring, resulting in pennycress yield equal to the no-cover treatments. However, a radish cover crop reduced pennycress yield compared to an oat cover crop when pennycress was planted in the spring (Table 4). Soybean seed yield and total oil seed yield was not affected ($p > 0.10$) by pennycress planting date, cover crop, or pennycress seeding rate. Overall pennycress yield in 2011 was lower in Exp. 2 compared to Exp. 1. This was likely due to a later fall planting date compared to Exp. 1 indicating that soybean yield was the primary factor driving total seed yield.

Rosemount 2012

Pennycress stands following establishment in fall 2011 were greater when pennycress was planted in August (8.9–15.5 30 cm^{-1} row) compared to September (0.4–1.4 30 cm^{-1} row) ($p < 0.0001$), regardless of cover or pennycress cultivar due to less precipitation occurring in August than September (Fig. 1). Pennycress growth was poor in the fall of 2011 (pennycress height less than 1 cm), similar to the other locations. When average over cultivars, pennycress stands at maturity were 12.0 to 17.2 plants 30 cm^{-1} of row with the greatest stand density occurring when pennycress was planted in August compared to September ($p = 0.06$). Companion cover crops reduced pennycress stand at harvest by 27 to 35% compared to pennycress alone ($p = 0.01$). Companion cover crops also reduce pennycress plant height when pennycress was planted in August but had no effect when pennycress was planted in September ($p = 0.003$). When averaged over cover crops, pennycress plants were 9% shorter when planted in September compared to August irrespective of pennycress cultivar ($p = 0.001$).

Pennycress seed yield was lower when planted in September compared to August regardless of pennycress variety or cover crop (Table 5). Pennycress seed yield was also reduced when planted with a companion cover regardless of planting date. MN106 pennycress cultivar produced more seed (1417.8 kg ha^{-1}) than the New York accession (1269.9 kg ha^{-1}) when planted without a cover ($p = 0.0001$). Soybean seed yield was lower when pennycress was planted in September compared to August, regardless of pennycress variety planted (Table 5). Soybean planted alone resulted in greater soybean yield compared to soybean double cropped with pennycress, but only at the late pennycress planting date. At the early planting date, pennycress did not influence soybean yield. Cover crop did not influence soybean seed yield. Total seed yield followed the same trends as pennycress seed yield with the exception of cover crop effects at the late pennycress planting date.

Lamberton 2012

The September pennycress planting date treatment was not implemented due to extremely dry soil conditions in fall 2011 at Lamberton. Therefore, no comparison was made of planting date effects at this location. Pennycress did not emerge following establishment in fall 2011 due to low soil moisture. However,

Table 5. Pennycress, soybean, and total seed yield as influenced by pennycress planting date and pennycress variety in Exp. 2 at Rosemount in 2012.

Treatment	Pennycress planting date					
	August	September	August	September	August	September
	Pennycress seed yield		Soybean seed yield		Total seed yield	
	kg ha^{-1}					
Pennycress line						
MN106	1245.4a†	796.4b	2822.8a	2528.7b	4068.2a	3325.1b
NY	1175.1a	798.9b	2853.3a	2503.1b	4028.4a	3272.0b
No PC‡	0c	0c	2890.4a	2938.0a	2890.4c	2938.0c
Cover crop						
PC	1128.7r	663.1st	ns§		4075.8r	3274.1stu
PC+Radish	588.8t	461.0u			3434.7st	3143.6u
PC+Oat	703.1s	441.2u			3476.5s	3117.4tu

† Means followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

‡ PC = pennycress.

§ ns = pennycress planting date × cover crop interaction was not significant.

Table 6. Total seed yield as influenced by cover crop and pennycress variety in Exp. 2 at Lamberton in 2012.

	Cover crop		
	PC	PC+Radish	PC+Oat
PC‡ Line	Total seed yield		
	kg ha^{-1}		
MN106	2079bc†	2103ab	2142ab
NY	2412a	2374ab	2331ab
No PC	1560d	2155ab	1693cd

† Means followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

‡ PC = pennycress.

Table 8. Weed biomass as influenced by pennycress variety and pennycress seeding date in Exp. 2 at Rosemount 2012.

	Weed biomass	
PC line	August	September
	g m^{-2}	
MN106	0.6c†	7.4c
NY	1.3c	3.8c
No PC‡	49.0b	101.3a

† Means followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

‡ PC = pennycress.

timely precipitation spring 2012 resulted in pennycress stands of 7 to 9 30 m^{-1} row and height of 36 to 48 cm at harvest. There was no difference in pennycress ($p = 0.34$) or soybean seed yield ($p = 0.48$) between cover crop treatments. Pennycress seed yield was also not affected by pennycress variety. However, soybean seed yield was greater when using the New York accession of pennycress (2132.9 kg ha^{-1}) compared to MN106 (1863.0 kg ha^{-1}) or the no pennycress treatments (1803.0 kg h^{-1}) ($p = 0.01$). Cover crop treatments had no effect on total seed yield regardless of pennycress variety used (Table 6). However, the New York accession of pennycress resulted in greater total seed yield than MN106 only when a cover crop was not used.

Weed Control as Influenced by Companion Cover Crop and Pennycress Seeding Rate, Planting Date, and Variety

Dominant weed species across all research sites included common lambsquarters (*Chenopodium album* L.), tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], and several annual grasses including giant foxtail [*Setaria faberi* (Herrm)] and green foxtail [*Setaria viridis* (L.) Beauv.]. At Rosemount, weed cover was significantly reduced in 2011 in both Exp. 1 and 2 when pennycress was present, especially at the higher seeding rate (Table 7). In 2012, weed biomass in Exp. 1 was reduced by >90% at Rosemount and >80% at Lamberton and Waseca when pennycress was present compared to no pennycress (Table 7). Pennycress seeding rate also had no effect on weed biomass across the three locations in 2012. In Exp. 2, weed biomass was reduced by >95% when pennycress was present regardless of pennycress variety or pennycress seeding date at Rosemount in 2012 (Table 8). At Lamberton, pennycress reduced weed biomass in the presence or absence of an oat companion cover crop in Exp. 2 (Table 9). When pennycress was not used, a radish or oat cover crop improved weed control compared to the no cover treatment. However, only a radish cover provided weed control similar to pennycress with or without a cover.

Table 7. Weed cover in 2011 and Weed biomass in 2012 as influenced by pennycress seeding rate.

	Pennycress seeding rate, kg ha^{-1}		
Experiment	0	5.5	11.0
	Weed cover, %		
Experiment 1 2011 Rosemount	46.1a†	22.2b	15.6c
Experiment 2 2011 Rosemount	51.1a	40.8b	35.6c
	Weed biomass, g m^{-2}		
Experiment 1 2012 Rosemount	97.7a†	4.4b	4.0b
Experiment 1 2012 Lamberton	38.9a	6.3b	6.2b
Experiment 1 2012 Waseca	74.6a	1.4b	1.1b

† Means in the same row and group followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

DISCUSSION

The first year of the study was characterized by above normal precipitation during pennycress establishment at Rosemount in fall 2010 followed by near normal precipitation spring 2011. Conversely, precipitation during fall 2011 was below normal during pennycress establishment followed by above normal precipitation in spring 2012 across all sites. Pennycress yield between field research sites tended to follow a precipitation gradient with relatively greater yield at Rosemount followed by Waseca and Lamberton, regardless of year.

Pennycress seeding rate had a direct effect on pennycress yield at Rosemount but not at Waseca or Lamberton locations. At Rosemount, a lower seeding rate of pennycress resulted in greater pennycress seed yield in 2011 (normal precipitation during fall establishment in 2010) whereas a higher rate resulted in greater yield in 2012 (below normal precipitation during fall establishment 2011). Planting a companion cover crop with pennycress resulted in stunted pennycress plants and lower yields at Rosemount but not at Waseca or Lamberton, especially in 2012. This suggests that competition between pennycress and companion cover crops for limited soil water negatively affected pennycress growth and yield, especially in years with below normal precipitation. This is supported by previous research suggesting that pennycress tends to have low water use efficiency (Anderson and Best, 1965). At Waseca and Lamberton, pennycress seed yield was not dependent on pennycress seeding rate or the use of companion covers, indicating that a lower seeding rate can be used at these sites and thus

Table 9. Weed biomass as influenced by cover crop and pennycress variety in Exp. 2 at Lamberton in 2012. Means within each group followed by the same letter are not significantly different ($p = 0.10$).

PC‡ variety	PC	PC+Radish	PC+Oat
	g m^{-2}		
MN106	3.8c†	2.0c	1.7c
NY	2.7c	1.7c	2.7c
No PC	61.7a	8.3bc	26.7b

† Means followed by the same letter are not significantly different at $p < 0.10$ by the Fisher's protected LSD test.

‡ PC = pennycress.

potential for lower seed costs and higher profitability. Lack of a companion cover crop effect at Waseca and Lamberton may have been due to relatively drier soil conditions at these locations in fall 2011 compared to Rosemount. As a result, oat and radish cover crops produced very little biomass and therefore reduced competition between pennycress and the cover crop. Pennycress likely out-competed these covers for resources resulting in no difference in pennycress yield when planted with or without a fall cover.

Pennycress seed yield was not influenced by a fall (November) or spring (April) planting date at Rosemount in 2011 when planted alone or with a radish cover. However, pennycress yield was greater when planted in the spring in the presence of an oat companion cover, suggesting that oat competed with pennycress in the fall while radish did not compete with pennycress. At Rosemount, pennycress yield in Exp. 2 was lower compared to yield in Exp. 1 which was likely due to a late fall planting date in Exp. 2 (November) compared to Exp. 1 (September). When exploring August or September planting date in Rosemount in 2012, pennycress yield was greatest when planted in August. In general, pennycress yield was greatest when planted in August or early September.

Previous research has shown no effect of pennycress on the subsequent soybean yield (Phippen and Phippen, 2012). In the present study, soybean yield results were mixed in that soybean yield was reduced when pennycress was planted in a double crop system at Rosemount, but not Waseca or Lamberton. Higher pennycress yields at Rosemount compared to other locations coupled with shallow, coarse textured soils likely reduced soil water availability in the subsequent soybean crop. A companion cover crop reduced soybean yield at Rosemount only in 2012. In this environment, radish reduced soybean yield but not oat.

The overall objective of a pennycress–soybean double cropping system is to increase seed production over that of a single crop system. In this study, the combined pennycress and soybean double cropping strategy produced more oil seed than each crop individually at these sites. Although soybean yield was reduced at Rosemount, the combined pennycress and soybean seed crop yield was greater, suggesting little production risk of using pennycress ahead of soybean. This result is similar to findings by Gesch and Archer (2013) who found that double cropping camelina (*Camelina sativa* L. Crantz) with soybean yielded more oil seed than soybean alone.

Pennycress significantly reduced weed cover in all locations and environments compared to treatments without pennycress. However, pennycress seeding rate or the use of a companion cover crop had little effect on weed suppression suggesting that a reduction in weed cover might be due in part to allelopathy and less with biomass production. Vaughn et al. (2006) found that pennycress meal reduced weed biomass by >90%. In exploring possible mechanisms of observed weed suppression, they noted that pennycress meal contains two allopathic chemicals that completely inhibited the germination of wheat, arugula, and sicklepod seeds (Vaughn et al., 2006).

Giant ragweed, common lambsquarters, and tall waterhemp pose a special risk to the upper Midwest corn–soybean system because of their propensity to develop herbicide resistance (Johnson et al., 2009). These weed species are prolific seed producers with seeds remaining in the soil seed bank for extended periods thereby maintaining herbicide resistance traits in the population (Burnside et al.,, 1996; Harrison et al., 2007; Owen, 2008). Integrated weed management strategies are being used to control existing weed populations as well as prevent herbicide resistant weed species from becoming established (Thill et al., 1991; Mortensen et al., 2012). Results of this research suggest that pennycress can be an important component of a comprehensive and integrated weed management strategy designed to prevent or suppress herbicide-resistant weed species. For example, fall establishment of pennycress followed by rapid growth in the spring, controlled early emerging weed species such as common lambsquarters and giant ragweed as well as late-emerging weed species such as tall waterhemp. Experiments were conducted in a geographic region where there is a growing interest in expanding ecosystem function while improving cropping system profitability. Therefore, the goal of this study was to explore the integration of pennycress and soybean crops as a means to increase overall oilseed production through approaches aimed at temporal intensification of agriculture. As a winter annual, pennycress also has the potential to provide early season weed control thereby increasing the value of pennycress in context of an integrated cropping system. Consequently, we analyzed a series of field experiments designed to capture information related to these goals. Preliminary results showing that a double cropping system of pennycress–soybean has potential to increase overall seed yield as well as decrease weed pressure within the cropping system. However these experiments were conducted across a limited geographic area and represent limited site-years. Future work in this area must strive to expand the geographic and temporal context of these findings as well as explore the economics of a pennycress–soybean double crop system.

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