Nitrogen use in double cropping soybean with non-fertilized winter oilseed crops

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Abstract: Sustainable intensification of cropping systems is a strategy to increase productivity and reduce disservices of conventional agroecosystems. Camelina [*Camelina sativa* (L.) Crantz] and field pennycress (*Thlaspi arvense* L.) are winter annual oilseed crops well suited to fill the fallow period between corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] in the U.S. northern Corn Belt, but their inclusion may be limited by resource use limitations. A 2-year study was conducted from 2015 to 2017 in the U.S. upper Midwest to evaluate the effect of double cropping on winter oilseed crops and soybean productivity and economic performance. Treatments included relay- and sequential-cropped soybean with winter camelina and field pennycress, and monocrop soybean as control. Biomass and grain yield of winter oilseed crops were not affected by cropping system. Averaged over years and cropping systems, winter camelina resulted in more biomass, nitrogen (N) uptake and grain yield by 240, 186 and 139% respectively, compared to field pennycress. Soybean biomass, N uptake and yield were higher in relay relative to sequential cropping. Relay soybean resulted in similar total grain yield (soybean + winter oilseed crop) compared to monocropped soybean. Double cropping soybean could maintain net return compared to monocropped soybean. Results indicate that double cropping winter oilseed crops with soybean can be economically viable in the U.S. upper Midwest. Yet, research aimed at optimizing yield through N and water use while improving ecosystem services is needed.
Keywords: camelina, pennycress, relay cropping, multiple cropping, winter oilseed
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1 Introduction

The U.S. upper Midwest has a 6-7 month fallow period between the corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.][1] rotation practice, resulting in environmental degradation[2]. This long fallow period is associated with soil erosion[3], reduction in soil organic carbon[4], and soil quality degradation[5]. The unprecedented increase in corn and soybean yield in the region is concomitant to agroecosystem disservices, such as N pollution of ground and surface water and soil degradation[6,7]. This evidences the challenges agriculture faces to ensure security of food, feed, fuel, and bio-based products for a growing global population and declining agricultural land[8] while minimizing environmental degradation. Innovative cropping systems may help ensure the sustainability of crop production.

Disservices from the simplified conventional corn-soybean rotation practice of the U.S. Midwest are frequently associated with poor nutrient cycling efficiency and water storage[9]. Diversified cropping systems are reported to improve such limitations[10,11]. Double cropping (relay- and sequential-cropping) is a sustainable intensification strategy to diversify crop production that is especially attractive to northern locations characterized by a short growing season and a long, cold winter[8,12,13]. The strategy could reduce nutrient loss[14], improve soil quality[15], decrease soil erosion[16], and increase biodiversity[17]. Camelina [*Camelina sativa* (L.) Crantz] and field pennycress (*Thlaspi arvense* L.), winter oilseed crops in the Brassicaceae family, have short life cycles[18], excellent winter survival[12], and high quality of seed oil[1,19]. Such characteristics make both crops promising prospects for double cropping with corn and soybean in northern climates[20,21].

Studies conducted in the region report that soybean-based double cropping systems have no effect on grain yield of winter oilseed crops, but productivity of soybean is reduced compared to its monocrop counterparts[8,13]. Gesch et al.[8] reported that soybean in relay yielded 17% to 42% less grain compared to its monocrop control but yielded more than in sequential cropping. However, other studies report that double cropping winter oilseed crops with soybean can still result in more total oilseed than monocropped soybean[20-22]. Furthermore, the net return of relay soybean with winter camelina is comparable to monocrop soybean but lower if when sequentially-cropped[8].

Studies on the water use of camelina-soybean in double cropping systems reported that camelina is a low water-use crop, mainly due to its marginal growth, shallow root system, and short lifecycle[12,23]. Furthermore, the ecological role of winter camelina double cropped with soybean clearly shows its potential to increase biodiversity[24], supply foraging resources to insects[18,25], and decrease soil erosion and nutrient loss[26]. However, little is known about resources use in diversified agroecosystems with winter

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oilseed crops, mainly N use of winter camelina and field pennycress in relay- and sequential-cropping systems and their impact on the overall productivity of soybean.

The objectives of this study were to determine the i) performance of low-input winter camelina and field pennycress in double cropping with soybean and ii) the effects of these crops on soybean N use, growth, yield, and economics in the U.S upper Midwest.

2 Materials and methods

2.1 Experimental design

The study was conducted from 2015 to 2017 at the University of Minnesota Southwest Research and Outreach Center located near Lamberton, MN (44°15′00′′N, 95°18′36′′W) on a moderately well-drained Normania clay loam soil (fine-loamy, mixed, superactive, mesic Aquic Hapludolls)[27]. The experiment was set as a randomized complete block in a split-plot arrangement with four replicates. The winter annual oilseed crops camelina and field pennycress were randomly assigned in main plots and cropping systems (mono-, relay-, and sequential-cropping) were assigned as subplots; the subplot size was 20 m by 6 m. Soybean was planted in relay and sequential-cropping at mid-flowering and after harvest of the winter oilseed crops, respectively. The control treatments consisted of monocrop soybean planted at the same time as soybean in the relay (Control relay) and sequential (Control sequential) cropping systems was planted. Further details of the study, including results of the effect of winter oilseed crops on double cropped corn, have been previously described in Liu et al.[12].

Winter oilseed crops were hand-broadcast and rake-incorporated during two growing seasons into standing corn on 31 August 2015 and 14 September 2016. Seeding rate for winter camelina (var. Joelle) and field pennycress (MN106) was 13 and 16 kg/hm^2, respectively. Early research has suggested that both crops respond positively to N[28,29]; however, both are also considered low-input crops[19]. Hence, to enhance agroecosystem services, no fertilizer was applied during the growth period of the winter oilseed crops. In both cropping systems, the winter oilseed crops were harvested on 17 June 2016, and 20 June 2017. After harvest, residue remained in the field for the relay cropping. For sequential cropping, residue was incorporated with disk tillage to a depth of 10 cm.

The soybean cultivar Stine 20RD20-2.0 MG was used at a population of 375 000 plants/hm^2 without fertilization. In the relay cropping, soybean was planted into winter oilseed crops without tillage on 19 May 2016 and 16 May 2017. In the sequential cropping, the seedbed was prepared with a disk harrow and soybean was planted on 22 June 2016, and 21 June 2017. Soybean was harvested on 3 November 2016, and 23 October 2017, and residue remained on the plots after harvest. All other cultural and agronomic practices were the same across treatments and based on guidelines (https://extension.umn.edu/crop-production#soybean) from the University of Minnesota.

2.2 Data collection

The aboveground biomass of winter oilseed crops was obtained prior to harvest. Winter oilseed crops biomass of 0.5 m^2 was taken and then dried in a forced air oven at 60°C to a constant weight. The seed yield of camelina and pennycress was hand-harvested at maturity in 0.5 m^2, yield was adjusted to 100 g/kg moisture. Soybean biomass was obtained manually by randomly harvesting 1 m length of row in each plot and weighing the aboveground mass. Soybean grain yield was obtained mechanically by harvesting the two central rows of each plot, and then adjusting the grain to 130 g/kg moisture. The plant biomass samples were ground to pass a 2 mm sieve and a subsample was analyzed for total N using a Vario Macro cube elementary analyzer (Elemental Analyzer vario MACRO cube, Germany). Seed protein content was obtained by NMR (Nuclear Magnetic Resonance, Minispec mq 20; Bruker, Ettlinggen, Germany) in 2017. Grain N content was calculated by dividing the protein content by 5.7[30].

For each treatment, the economic analysis was performed according to the inputs and field operations. Chemical costs corresponded to the average of 2016 and 2017 for Southwest Minnesota from the University of Minnesota Extension (104.57 \$/hm^2; https://finbin.umn.edu/). The seed cost of winter camelina and field pennycress was set at 44.48 \$/hm^2[12]. Soybean seed cost was based on actual costs. The cost of machinery was based on Lazarus[31]. The cost of fuel, lubricants, repair and maintenance, labor, power, implement depreciation and overhead (interest, insurance and housing) were included in machinery costs. Planting cost included a no-till drill and combine grain head rather than labor for hand planting and harvesting of winter oilseed crops[31]. Soybean grain price corresponded to the average of 2016 and 2017 annual prices in Minnesota (0.34 \$/kg)[32]. The grain prices of winter oilseed crops were set as \$0.40/kg according to the average of canola grain price in Minnesota from 2012-2017[32]. The cost for land, crop insurance, storage, and drying was not considered because these were the same across treatments.

2.3 Statistical analysis

All data were subjected to ANOVA using R version 3.5.3 (R Foundation for Statistical Computing, Vienna, Austria). Visual representations were used to check the normality of data. Winter oilseed crop type, cropping system and year were treated as fixed effects, and replication was treated as random effect. Post hoc Fisher's protected Least Significant Difference was performed to separate means when treatments were significant at $p = 0.05$.

3 Results and discussion

3.1 Weather conditions

Weather data were arranged from September through August to represent the growing season of winter annual oilseed and soybean crops. The 2015-2016 seasons were slightly warmer than 2016-2017, especially during December, March and August (Table 1). Both growing seasons were warmer than the long-term average. The total precipitation during the growing seasons was 927 mm and 829 mm in 2015-2016 and 2016-2017, respectively; around 80% of total precipitation occurred from May to September. Total precipitation during the study years was 34% and 20% greater than the long-term average. The amount of precipitation during the 2015-2016 and 2016-2017 winter oilseed crops growing season was 592 mm and 507 mm, respectively. The accumulated precipitation during the 2016 and 2017 soybean growing season was 688 mm and 611 mm respectively in relay cropping, and 520 mm and 449 mm respectively in sequential cropping (Table 1).

3.2 Biomass yield and N uptake of winter oilseed crops

Biomass and N uptake of winter oilseed crops were significantly affected by type of winter oilseed crop and year (Table 2). The difference in biomass of relay and sequential oil seed crops was not significant, indicating no effect of soybean on growth of both winter camelina and field pennycress. The biomass and N uptake of the winter oilseed crops was much lower in 2016 than 2017. This could be explained by the wetter March of 2016 that negatively affected the growth of both winter oilseed crops (Table 1).

Table 1 Long-term (1980-2014) and growing season (2015-2016 and 2016-2017) weather conditions at Lamberton, MN

Month	1980-2014				2015-2016				2016-2017			
	T_{max}/°C	T_{min}/°C	T_{avg}/°C	Precipitation/(mm·mon^{-1})	T_{max}/°C	T_{min}/°C	T_{avg} /°C	Precipitation/ (mm·mon^{-1})	T_{max}/°C	T_{min}/°C	T_{avg}/°C	Precipitation/(mm·mon^{-1})
Sep	23.2	8.9	16.0	80	26.0	12.9	19.5	87	23.5	11.9	17.7	134
Oct	15.6	2.0	8.8	49	17.2	3.5	10.3	43	16.7	3.5	10.1	72
Nov	5.7	–5.1	0.3	30	9.5	–1.3	4.1	84	10.9	–0.1	5.4	47
Dec	–2.5	–12.5	–7.5	18	0.8	–6.1	–2.7	35	–3.4	–13.0	–8.2	29
Jan	–4.3	–15.2	–9.7	14	–4.6	–13.9	–9.2	8	–4.0	–11.4	–7.7	12
Feb	–1.9	–12.7	–7.3	15	–0.4	–8.5	–4.4	17	5.1	–6.4	–0.7	2
Mar	4.5	–6.0	–0.7	39	8.7	–1.4	3.7	51	4.9	–5.6	–0.4	10
Apr	13.9	0.9	7.4	74	14.8	2.5	8.7	85	14.2	2.6	8.4	77
May	21.3	8.1	14.7	90	21.6	7.8	14.7	141	19.5	7.8	13.6	152
Jun	26.5	13.9	20.2	108	27.4	15.3	21.4	66	27.0	14.4	20.7	69
Jul	28.7	16.0	22.3	87	27.7	16.6	22.1	176	28.7	16.1	22.4	102
Aug	27.2	14.3	20.7	91	27.0	15.8	21.4	135	24.3	13.4	18.8	125

Table 2 Significance of *F* value for fixed sources of variation for biomass, N uptake, grain yield of crops and net income

Source of variation	Biomass yield			N uptake			Grain yield			Net income
	Winter oilseed crop	Soybean	Total	Winter oilseed crop	Soybean	Total	Winter oilseed crop	Soybean	Total	
Winter oilseed crop type (OT)	***	**	***	***	ns	ns	***	ns	**	ns
Crop system (CS)	ns	***	***	**	***	***	ns	***	***	***
Year (Y)	***	***	ns	***	**	ns	**	ns	ns	ns
OT × CS	ns	ns	*	*	ns	ns	ns	*	*	*
Y × OT	**	ns	ns	***	ns	ns	*	ns	**	**
Y × CS	ns	***	**	ns	*	*	ns	***	***	***
Y × OT × CS	ns	*	ns	ns	ns	ns	ns	ns	ns	ns

Note: ns, *, **, *** indicates not significant, and significant at p = 0.05, 0.01, 0.001, respectively.

The average biomass and N uptake of field pennycress was 71% and 65% lower, respectively than camelina across the 2-year study period. This may have been due to its poor establishment because of seed dormancy, which has been reported as a major obstacle to strong stand establishment, performance, and yield[1,33]. In addition, field pennycress establishment could also be affected by temperature and light[34]. Earlier studies have reported that seed germination and emergence of field pennycress can be inhibited by moisture stress and indirect or filtered light, respectively[35]. In this study, field pennycress was seeded into R5-R6 corn stages of development, overlapping for 38 d in 2015 and 45 d in 2016 before corn harvest. The reduced light through the corn canopy may have reduced pennycress seedling emergence.

Soybean biomass and N uptake were significantly affected by cropping system and year (Table 2). The differences between years were partially due to the greater precipitation of 2016 soybean growing season compared to 2017. Relay cropping significantly lowered soybean biomass compared to monocropped soybean in 2017, but sequential cropping did not affect soybean biomass in either year (Table 3).

Table 3 Crop biomass, N uptake and grain yield from different cropping systems during the 2015-2016 and 2 016-2 017 growing seasons at Lamberton, MN

Cropping System¶	Aboveground biomass			N uptake			Grain yield		
	Winter oilseed crop/ kg·hm^{-2}	Soybean/ t·hm^{-2}	Total/ t·hm^{-2}	Winter oilseed crop/ kg·hm^{-2}	Soybean/ kg·hm^{-2}	Total/ kg·hm^{-2}	Winter oilseed crop/ kg·hm^{-2}	Soybean/ t·hm^{-2}	Total/ t·hm^{-2}
2015-2016									
Camelina-soybean-relay	1531b‡	11.3a	12.8a	22b	287b	309ab	247ab	3.2b	3.5a
Camelina-soybean-sequence	2871a	6.5b	9.4b	42a	180c	222c	480a	2.2cd	2.7b
Pennycress-soybean-relay	776c	12.0a	12.8a	16b	327a	343a	245ab	3.5ab	3.8a
Pennycress-soybean-sequence	799c	7.0b	7.8c	15b	193c	208c	191b	2.0d	2.2d
Control relay	-	12.1a	12.1a	-	298ab	298b	-	3.6a	3.6a
Control sequential	-	7.6b	7.6c	-	213c	213c	-	2.4c	2.4bc
2016-2017									
Camelina-soybean-relay	3760a	8.7b	12.5a	56a	242ab	298a	735ab	2.7ab	3.5a
Camelina-soybean-sequence	3840a	7.5bc	11.3a	76a	194b	270ab	786a	2.7ab	3.5a
Pennycress-soybean-relay	1089b	7.7bc	8.8b	17b	204b	221bc	142c	3.0a	3.2a
Pennycress-soybean-sequence	870b	7.2c	8.0b	21b	189b	210bc	362bc	2.7ab	3.1a
Control relay	-	11.4a	11.4a	-	291a	291a	-	3.0a	3.0a
Control sequential	-	7.4bc	7.4b	-	197b	197c	-	2.3b	2.3b

Note: ¶Control relay: Relay control; soybean planted at the same time soybean was no-till planted in relay cropping with winter oilseed crops; Control sequential: Sequential control; soybean planted at the same time soybean was no-till planted in sequential cropping with winter oilseed crops; ‡Within a year, column values followed by different letters differ significantly different at p<0.05.

Winter camelina in relay cropping resulted in similar total biomass (winter oilseed crop + soybean) compared with monocropped soybean, indicating the winter camelina biomass could compensate for the soybean biomass reduction (Table 3). In sequential cropping with winter camelina, total biomass significantly increased compared to monocropped soybean. Field pennycress maintained total biomass compared to monocropped soybean in the sequential cropping system. Total biomass in both relay- and sequential-cropping increased significantly with winter camelina in three of four sampling times, compared to pennycress. Relay cropping resulted in greater total N uptake compared to sequential cropping (Table 2).

3.3 Grain yield of crops

The grain yield of winter oilseed crops was significantly affected by crop type and year (Table 2). Averaged across years and cropping systems, winter camelina yielded 39% more than pennycress (Table 3). This may have been due to the seed dormancy in pennycress, which may have decreased emergence, establishment, and yield[1]. Seed dormancy in field pennycress is reported to mask environmental effects on germination and emergence[1,33] which may be a positive trait when interseeding due to better timing with summer crop senescence[36]. Cropping systems had no effect on grain yield of winter oilseed crops (Table 2). This is supported by previous research that showed double cropping camelina with soybean resulted in a similar yield[8]. Relay soybean was intercropped at mid-flowering stage of winter oilseed crops.

In the present study, winter camelina grain yield ranged from 247 to 786 kg/hm^2 (Table 3). Our results are within the range of previous studies reporting non-fertilized yield between 394 and 703 kg/hm^2[12,37]. While grain yield of unfertilized winter camelina from this and other studies is low, the addition of N fertilizer could results on yield as high as 1939 kg/hm^2[13,20,25], suggesting that winter camelina responds positively to N application.

Soybean grain yield was affected by cropping system and by the winter oilseed crop type × crop system and year × crop system interactions (Table 2). Averaged across the two years, soybean in relayed produced 34% more yield than sequential. Our results are supported by those from Gesch et al.[8] on double-cropping soybean with winter camelina, who report that yield of soybean in relay increased by 33% to 70% compared to sequential. Late planting negatively affects soybean yield[38]. In this study, sequential soybean was planted ~35 d later than the relay cropping (mid-May), which was outside the late April to mid-May optimum planting date for conditions in the U.S. upper Midwest[38,39]. While sequential cropping is an attractive practice, the combination of a shortened growing and precipitation lower than the long-term average, both reported to affect soybean yield[40], were likely the main factors contributing to soybean yield reduction.

The winter oilseed crop type had no significant effects on soybean yield (Table 2). In west central Minnesota, Gesch et al.[8] showed that soybean in relay with camelina resulted in 17% to 42% reduction in soybean yield compared to its monocropped counterpart. However, a multi-location study on double cropping soybean with winter camelina and field pennycress conducted in Minnesota reported that both winter oilseed crops had no impact on the productivity of soybean[26]. Results from this study indicated that the 30-36 d of overlapping crop growth in the relay system had no effect on the productivity of soybean. Our findings support those by Ott et al.[41] who reported similar results.

Total grain yield (soybean + winter oilseed crop) was affected by winter oilseed crop type, cropping system, and the winter oilseed crop type × cropping system, and year × winter oilseed crop type and year × cropping system interactions (Table 2). The use of winter oilseed crops in relay-cropping resulted in similar total yields compared to monocropped soybean (Table 3). In sequential-cropping, winter oilseed crops increased total yield compared to monocropped soybean in 2017 (Table 3).

3.4 Cropping systems economics

The cost of the control treatment of the relay-cropping system was lower than that of the sequential-cropping, mainly due to the tillage in the latter (Table 4). The addition of winter oilseed crops increased costs compared to monocropped soybean in both relay- and sequential-cropping systems, due to the extra costs associated with seed, planting and harvest of winter oilseed crops. Relay-cropping significantly increased net income compared to sequential-cropping (Table 2). This was primarily due to higher soybean grain yield in the former. The use of winter oilseed crops did not affect net income compared to monocropped soybean, indicating that grain income of winter oilseed crops could compensate for the added production costs. These findings support previous studies showing that relay-cropping soybean with winter camelina may result in net return competitive with monocropped soybean[8].

Table 4 Production costs and net income for different treatments during the 2015-2016 and 2016-2017 growing seasons

Growing Season	Cropping system[a]	Cost/\$·hm^{-2}[b]			Income[c] /\$·hm^{-2}	
		Material	Machinery	Total	Gross	Net
2015-2016	Camelina-soybean-relay	297	283	581	1187a[‡]	607b
	Camelina-soybean-sequence	297	312	609	937b	329c
	Pennycress-soybean-relay	297	283	581	1285a	705ab
	Pennycress-soybean-sequence	297	312	609	759c	150d
	Control relay	253	156	409	1230a	822a
	Control sequential	253	184	437	801bc	364c
2016-2017	Camelina-soybean-relay	297	283	581	1223a	643a
	Camelina-soybean-sequence	297	312	609	1219a	610ab
	Pennycress-soybean-relay	297	283	581	1082a	501ab
	Pennycress-soybean-sequence	297	312	609	1072a	463ab
	Control relay	253	156	409	1019ab	611ab
	Control sequential	253	184	437	781b	344b

Note: [a] Control relay: Relay control; soybean planted at the same time soybean was no-till planted in relay cropping with winter oilseed crops; Control sequential: Sequential control; soybean planted at the same time soybean was no-till planted in sequential cropping with winter oilseed crops.

[b]Material cost include cost of seed and herbicide; Machinery cost include cost of fuel, lubricants, repair and maintenance, labor, power, implement depreciation, and overhead (interest, insurance and housing); Total cost = Material cost + Machinery cost.

[c]Gross income = winter oilseed crop yield × price + soybean grain yield × price; Net income = gross income – Total cost.

[‡]In a column and within a year, values followed by different letters differ significantly at $p < 0.05$.

The results showed that using winter oilseed crops as a diversification strategy in soybean production practices is economically feasible in the region. Additional benefits expected from this strategy include ecosystem services such as increased land cover, reduced soil erosion and nutrients loss, improved soil quality, and overall improved resources use efficiency.

4 Conclusions

This study was conducted to evaluate the growth, N uptake and economics of winter camelina and field pennycress double cropped with soybean and the effects of these winter oilseed crops on productivity of the major crop. The biomass and grain yield of a given winter oilseed crop was similar in both relay- and sequential-cropping systems. Winter camelina had higher biomass, N uptake and grain yield than field pennycress. Soybean biomass, N uptake and grain yield were affected by cropping system. Winter camelina and field pennycress did not affect N uptake or grain yield of soybean. Winter oilseed crops maintained or increased total grain yield (soybean + winter oilseed crop) in both relay- and sequential-cropping systems; however, winter oilseed crops had no effect on the net return of double cropped soybean.

Overall, both relay and sequential cropping systems could maintain soybean grain yield and net return compared to monocrop soybean in northern locations. Further research is needed to develop technologies that increase the grain yield of winter oilseed crops and optimize the economic return of diversified soybean production systems in intensively cultivated regions. Special attention might be needed when adding N into winter oilseed crops within double cropping systems. This is specially important in locations where conventional agroecosystems have high loads of external inputs.

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