Potential of Relay-Cropping Soybean (Fabales: Fabaceae) with a Pennycress (Brassicales: Brassicaceae) Cover Crop to Suppress Soybean Aphid (Hemiptera: Aphididae) Populations[1]

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Abstract The soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), remains a major pest of soybean, *Glycine max* (L.) Merrill (Fabales: Fabaceae), production in the Upper Midwest, leading to yield losses of up to 40% and it has developed resistance to some insecticides. These challenges underscore the necessity for more integrated pest management approaches, such as cultural control methods. Relay-cropping soybean with a winter cover crop has the potential to suppress some soybean pest populations. Field pennycress or pennycress, *Thlaspi arvense* L. (Brassicales: Brassicaceae), is currently being domesticated as a new cover crop and oilseed crop. In this study, we evaluated the impact of relay-cropping soybean into a pennycress cover crop on soybean aphid populations across 4 site-years in Minnesota. The experimental design included combinations of two soybean varieties planted with and without pennycress. Soybean aphid populations were monitored weekly by counting aphids on 10 randomly selected soybean plants per plot. Although aphid infestations were relatively low across the site-years, the results demonstrated that soybean relay-cropped with pennycress had lower seasonal aphid abundance (i.e., cumulative aphid-days) than soybean without the cover crop. These findings indicate that relay cropping soybean into pennycress cover crops holds promise as a cultural control tactic to reduce soybean aphid populations, providing a more sustainable pest management option for growers.

Key Words pest management, pennycress, relay-cropping, cultural control, ecological impact

In the Upper Midwest, annual crop rotations, typically including corn, *Zea mays* L. (Poales: Poaceae), and soybean, *Glycine max* (L.) Merrill (Fabales: Fabaceae), rely heavily on external inputs and have a prolonged fallow period between growing seasons (Rusch et al. 2020). During this fallow time, the soil is at risk of erosion and valuable nutrients may leach or runoff into nearby water bodies (Rusch et al. 2020). Introducing winter cover crops into such rotations can help mitigate these issues and enhance the sustainability of the farming system (Cubins et al. 2019, Rusch et al. 2020).

Thlaspi arvense L. (Brassicales: Brassicaceae), commonly known as pennycress or field pennycress, grows as a weed across temperate regions of North America, but is being developed as a new cash cover crop (Cubins et al. 2019, Mitich 1996, Moser et al. 2009, Sedbrook et al. 2014). In addition to providing ecological services

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as a cover crop, pennycress produces an oilseed that can be harvested and provide direct economic benefit to farmers (Bishop and Nelson 2019, Cubins 2019, Cubins et al. 2019, Phippen and Phippen 2012). A survey found that >58% of farmers in the Midwest are interested in planting pennycress (Basnet and Ellison 2024).

Pennycress can be integrated into rotations, such as corn–soybean or wheat–soybean, as a winter cover crop (Cubins 2019, Cubins et al. 2019, Ott et al. 2019, Phippen and Phippen 2012). After the harvest of wheat, *Tritium aestivum* L. (Poales: Poaceae), or corn in the summer or fall, respectively, pennycress is planted. The pennycress germinates and establishes itself before winter, providing ground cover during fall, winter, and spring. Soybean is then double-cropped by planting after pennycress harvest in the early summer, or relay-planted directly into standing pennycress in late spring. Harvest of pennycress in relay-cropping systems occurs by cutting the pennycress above the growing soybean (Cubins 2019, Cubins et al. 2019, Moore et al. 2022, Ott et al. 2019, Phippen and Phippen 2012).

The use of cover crops, particularly in reduced-tillage systems, can impact arthropod populations through various mechanisms (Scavo et al. 2022, Schmidt et al. 2018, Tillman et al. 2004). The spatial-temporal overlap of the 2 crops (e.g., pennycress and soybean) in relay-planting creates a polyculture, as opposed to the typical monoculture (e.g., soybean alone). Polycultures can reduce herbivore densities by decreasing the likelihood of a pest finding or remaining on a particular plant (i.e., resource concentration hypothesis; Root 1973). Polycultures can also enhance the presence and effectiveness of natural enemies of pests, thereby reducing pest populations (i.e., natural enemies hypothesis; Root 1973). In addition, polycultures can change the quality of host plants as a result of interspecific plant interactions, leading to reduced pest densities (Altieri and Letourneau 1982).

In the Upper Midwest, soybean continues to face significant challenges from soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae) (Koch et al. 2018, Ragsdale et al. 2007). This pest can cause up to 40% yield loss and result in significant economic loss to soybean growers (Ragsdale et al. 2007). Native to Asia, soybean aphid was first detected in North America in Wisconsin in 2000 and quickly spread across most of the soybean-growing areas (Ragsdale et al. 2011). This species alternates between primary hosts, such as common buckthorn, *Rhamnus cathartica* L. (Rosales: Rhamnaceae), on which it sexually reproduces and overwinters, and secondary hosts, including soybean, on which it asexually reproduces and can cause economic damage during the growing season (Ragsdale et al. 2004, Tilmon et al. 2011). Feeding by the soybean aphid is linked to decreased plant height, fewer pods, smaller seed size and quality, and lower crop yields (Ragsdale et al. 2007, Beckendorf et al. 2008, Catangui et al. 2009).

Since 2000, the soybean aphid has been intensively managed due to its potential for significant economic damage (Song and Swinton 2009). Although various pest management strategies exist, including host plant resistance and biological control, the predominant method remains the use of foliar insecticides (Hodgson et al. 2012; Koch et al. 2015, 2018). However, another management strategy that has garnered interest is the deployment of cover crops as a cultural control to reduce soybean aphid populations (Heimpel et al. 2005, Koch et al. 2012). Research has shown that the population of soybean aphids can be suppressed when soybean is relay-cropped into a winter rye, *Secale cereale* L. (Poales: Poaceae), cover crop (Koch et al. 2012, 2018).

Despite the recognized benefits of cover crops for soil health and pest management, their adoption by farmers has been minimal, at 7.2% across the Midwest (Burnett et al. 2018, Cubins et al. 2019, Dunn et al. 2016, Scavo et al. 2022, Zhou et al. 2022). However, there is a growing interest in and a higher potential for the adoption of pennycress as a cover crop due to its combined benefits as a cover crop and oilseed crop (Burnett et al. 2018, Cubins et al. 2019, Dunn et al. 2016, Scavo et al. 2022). Given this increasing interest, the objective of this study was to evaluate the potential effects of relay-cropping soybean with a pennycress cover crop on soybean aphid populations across multiple site-years in Minnesota.

Materials and Methods

This study was conducted at the University of Minnesota's Rosemount Research and Outreach Center, Rosemount, MN (44°43′N, 93°04′W; 294 m above sea level) in 2022 and 2023; the USDA-ARS Swan Lake Research Farm, Morris, MN (45° 40′N, 95°48′W; 345 m above sea level) in 2022; and the University of Minnesota Experiment Station at St. Paul, MN (44°59′N, 93°10′W; 294 m above sea level) in 2023. The soil at Rosemount, Morris, and St. Paul were Waukegan silt loam (i.e., 0–1% slope, fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll), Aazdahl-Formdale-Balaton clay loam (i.e., fine-loamy, mixed, superactive, frigid Aquic Hapludoll), and Waukegan silt loam (i.e., 0–2% slope, fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll.), respectively (Soil Survey Staff, Natural Resources Conservation Service, USDA 2024). In 2022, the annual average temperature and liquid precipitation for Rosemount and Morris was 6.1 and 5.4°C and 75.8 and 56.1 cm, respectively (ARS, USDA 2023). In 2023, the annual average temperature and liquid precipitation for Rosemount and St. Paul was 8.2 and 8.3°C and 96.0 and 96.6 cm, respectively (ARS, USDA 2023). The plant hardiness zones for Rosemount, Morris, and St. Paul are 5a, 4b, and 5a, respectively (ARS, USDA 2023).

The treatments evaluated for this study were a subset of a larger experiment that was conducted using a split-plot design with the presence or absence of pennycress as a whole-plot factor and soybean variety as the split-plot factor at 4 site-years (L.M.R. and A.L. unpubl. data). Pennycress genotype 'MN106NS,' a black-seeded variety originally collected in Coates, MN, with minimal silicle shattering (Dorn et al. 2013, 2015), was used as the cover crop treatment across all site-years. Pennycress seed was sown at 11.21 kg/ha after harvest of spring wheat on 13 September 2021 at Rosemount and 17 September 2021 at Morris and on 26 September 2022 at Rosemount and 30 September 2022 at St. Paul. At Rosemount 2022, Morris 2022, and Rosemount 2023, pennycress was planted 0.3 cm deep in multiple passes of the planter with 3 rows of pennycress planted 19 cm apart and a skip row where soybean would be planted between each set of 3 rows of pennycress, so that 3 rows of pennycress would separate each row of soybean. At St. Paul 2023, pennycress was broadcast seeded with an alfalfa seeder. In early spring when pennycress growth resumed, 56.04 kg/ha of nitrogen in the form of urea was applied.

In years 1 and 2 of the larger experiment, 40 and 8 soybean genotypes, respectively, were used as the split-plot factor at each site. For the present study, two commercial soybean genotypes 'BS1146' and 'AgriGold G1502RX' were chosen for sampling. BS1146, developed by Brushvale Seed Inc. (Breckenridge, MN), is a conventional food-type soybean with large seeds and high protein. AgriGold G1502RX, developed by AgReliant Genetics LLC (Westfield, IN), is tolerant of glyphosate and dicamba herbicides. Both varieties have tolerance to soybean cyst nematode (*Heterodera glycines*) and are similar in their maturities (1.1 and 1.5 relative maturities for BS1146 and AgriGold G1502RX, respectively). No insecticide or fungicide seed treatments were used on the soybean seed. Plots were planted 3.8 cm deep at a seeding rate of 170,512 seeds per ha on 10 and 26 May 2022 at Rosemount and Morris, respectively, and on 5 June and 31 May 2023 at Rosemount and St. Paul, respectively. Soybean plots consisted of 4 rows 3.6 m long and spaced 0.76 m apart. For the whole-plot treatment with soybean relay-cropped into pennycress, soybean was planted into standing pennycress at the early flowering growth stage of the pennycress. For the whole-plot treatment without relay cropping, soybean was planted into a conventionally tilled field with minimal wheat residue from the previous year's corn crop. After the emergence of soybean, pennycress was harvested on 23 and 28 June 2022 at Rosemount and Morris, respectively, and on 11 July 2023 in St. Paul. However, pennycress was not harvested at Rosemount 2023 due to short pennycress plant height caused by limited rainfall during pennycress growth. Foliar pesticides were not applied to the plots.

To determine the abundance of soybean aphids in the research plots, each plot was sampled weekly during the growing season for soybean. On each sample date, 10 soybean plants were randomly selected from the middle 2 rows of each plot and nondestructive visual whole-plant inspections were performed to quantify soybean aphids. Soybean aphid counts included nymphs and winged and wingless adults. Aphid counts were then summarized as cumulative aphid-days (CAD; Hanafi et al. 1989) by using the following formula:

$$\mathrm{CAD} = \sum_{i=1}^{n} \left[\frac{(x_i + x_{i+1})}{2}\right] \times (t_i - t_{i-1}),$$

where x_i is the mean number of aphids per plant on a given sample date *i* and $(t_i - t_{i-1})$ is the number of days between 2 consecutive sample dates.

Analyses were performed using R 4.2.0 (R Core Team 2022) in RStudio (RStudio Team 2022). To evaluate the overall impacts of the cover crop and soybean varieties on soybean aphids, a combined analysis was conducted across all 4 site-years by using a linear model (package: stats, code: aov) with CAD as the response variable and cover crop (presence or absence), soybean variety (BS1146 or AgriGold G1502RX), site-year, block nested within site-year, and all two- and three-way interactions between cover crop, soybean variety, and site-year as predictors. The significance of effects was assessed with analysis of variance (package: car, code: Anova), and backward selection was used to remove nonsignificant ($P > 0.10$) interactions.

To assess the effects of cover crops and soybean varieties on soybean aphid populations for each site-year, separate analyses were performed using linear models (package: stats, code: aov) with CAD as the response variable and cover crop (presence or absence), soybean variety (BS1146 or AgriGold G1502RX), block, and the two-way interaction between cover crop and variety as predictors.

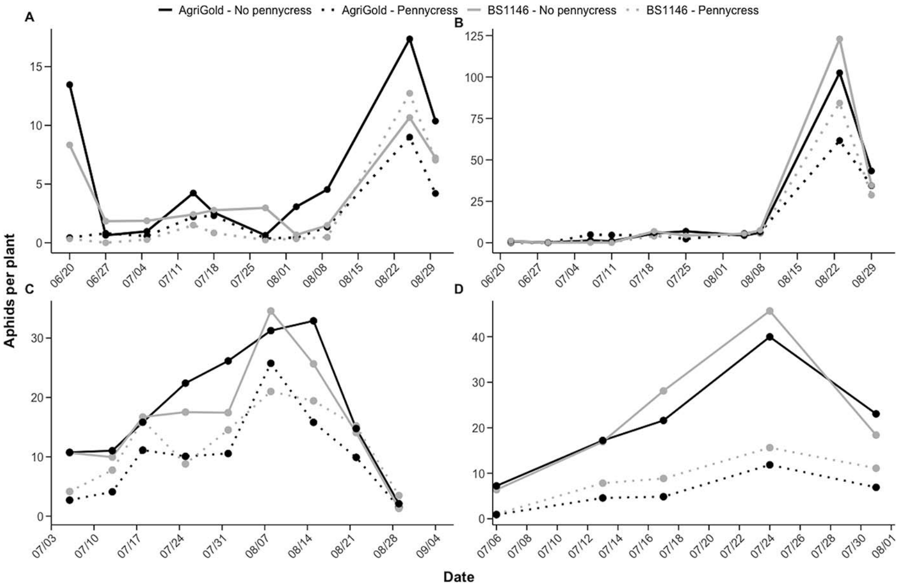

Fig. 1. Mean aphid density (aphids per plant) over time on two soybean varieties (AgriGold G1502RX and BS1146) relay-cropped with pennycress or no pennycress at Rosemount 2022 (A), Morris 2022 (B), Rosemount 2023 (C), and St. Paul 2023 (D).

The significance of effects was assessed with analysis of variance (package: car, code: Anova), and backward selection was used to remove nonsignificant ($P > 0.10$) interactions.

Results

Through backward selection performed on the full model for the analysis across site-years, the three-way interaction between cover crop, soybean variety, and site-year and the two-way interactions between cover crop and soybean variety and between soybean variety and site-year were removed, and associated variances were pooled into error variance. In the reduced model, the interaction between cover crop and site-year was marginally significant ($F = 2.719$; df = 3, 33; $P = 0.06$), suggesting that the effect of cover crop on CAD differed among site-years. The main effect of cover crop had a significant effect on CAD ($F = 35.696$; df = 1, 33; $P < 0.001$), with lower CAD in plots with pennycress than in plots without pennycress. However, soybean variety ($F = 0.861$; df = 1, 30; $P = 0.36$) and block nested in site-year were not significant ($F = 1.048$; df = 10, 30; $P = 0.43$).

Because of the marginally significant interaction between cover crop and site-year described above, each site-year was analyzed separately. At Rosemount 2022, mean aphid densities ranged from 0 to 17.4 aphids per plant per date across treatments and sample dates, with the peak density occurring on 25 August (Fig. 1A). Soybean varieties relay-cropped with the pennycress cover crop had lower CAD than

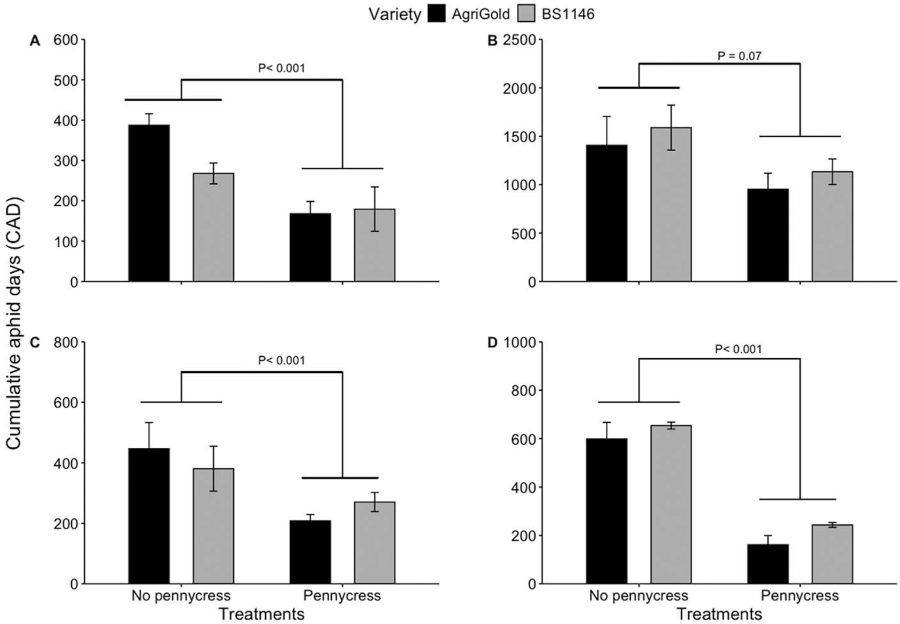

Fig. 2. Mean (±SE) cumulative aphid-days (CAD) for soybean aphid on two soybean varieties (AgriGold G1502RX and BS1146) relay-cropped with pennycress or no pennycress at Rosemount 2022 (A), Morris 2022 (B), Rosemount 2023 (C), and St. Paul 2023 (D).

soybean varieties without the pennycress cover crop ($F = 17.4$; df $= 1, 4$; $P < 0.001$) (Fig. 2A). The effects of soybean variety ($F = 2.2$; df $= 1, 4$; $P = 0.18$) and the interaction between soybean variety and cover crop ($F = 3.2$; df $= 1, 4$; $P = 0.11$) were not significant.

At Morris 2022, mean aphid densities ranged from 0 to 123.0 aphids per plant per date across treatments and sample dates, with the peak density occurring on 23 August (Fig. 1B). Soybean varieties relay-cropped with the pennycress cover crop had marginally lower CAD than soybean varieties without the pennycress cover crop ($F = 4.42$; df $= 1, 4$; $P = 0.07$) (Fig. 2B). The effects of soybean variety ($F = 0.70$; df $= 1, 4$; $P = 0.43$) and interaction ($F = 0.00$; df $= 1, 4$; $P = 0.10$) were not significant.

At Rosemount 2023, mean aphid densities ranged from 0.3 to 34.3 aphids per plant per date across treatments and sample dates, with the peak density occurring on 8 August (Fig. 1C). Soybean varieties relay-cropped with the pennycress cover crop had lower CAD than soybean varieties without pennycress cover crop ($F = 1.8$; df $= 1, 8$; $P < 0.001$) (Fig. 2C). The effects of soybean variety ($F = 0.00$; df $= 1, 8$; $P = 0.97$) and the interaction between soybean variety and cover crop ($F = 1.14$; df $= 1, 8$; $P = 0.30$) were not significant.

At St. Paul 2023, mean aphid densities ranged from 0.9 to 45.7 aphids per plant per date across treatments and sample dates, with the peak density occurring on 24 July (Fig. 1D). Soybean varieties relay-cropped with the pennycress cover crop had lower CAD than soybean varieties without pennycress cover crop ($F = 113.8$; df = 1, 8; $P < 0.001$) (Fig. 2D). The effects of soybean variety ($F = 2.95$; df = 1, 8; $P = 0.11$) and the interaction between soybean variety and cover crop ($F = 0.11$; df = 1, 8; $P = 0.74$) were not significant.

Discussion

Across the 4 site-years of this study, soybean varieties relay-cropped with pennycress exhibited lower soybean aphid pressure (i.e., CAD) for soybean aphid than soybean varieties without pennycress. Similarly, Koch et al. (2012, 2015) and Lundgren et al. (2013) found that relay-cropping soybean with rye led to reductions in soybean aphid densities. Schmidt et al. (2007) documented reductions in soybean aphid infestations when soybean was planted into a living mulch of alfalfa, *Medicago sativa* L. (Fabales: Fabaceae). There were no effects of soybean variety or interactions between soybean variety and cover crop on soybean aphid populations. Previous research has shown no effect of soybean variety on aphid numbers for varieties without aphid resistance genes (Rag genes; Hanson et al. 2017). Overall, the results presented herein, and supported by similar research, highlight the potential for relay-cropping soybean into pennycress as a potential cultural control tactic for soybean aphid management.

Although it remains unknown how pennycress affected soybean aphid populations on soybean, various mechanisms have been proposed to explain the differences in herbivore populations between polycultures and monocultures (Bröcher et al. 2023). According to the resource concentration hypothesis, herbivores are more likely to locate and stay on a host plant in monocultures than in polycultures, leading to higher population densities in monocultures (Root 1973). In addition, the polyculture created by planting soybean into the cover crop may support more diverse communities of natural enemies that could help control aphid populations (Scavo et al. 2022, Schmidt et al. 2018, Tillman et al. 2004). If soybean were implemented in a double-cropping system with pennycress, we would expect to see less impact on insect pests, such as soybean aphid, because there would no longer be co-occurrence of both species (i.e., a polyculture). However, further research is needed to understand the mechanisms affecting the dynamics of pest populations in such a system.

By leveraging the pest suppression offered by relay cropping into cover crops, farmers may be able to reduce reliance on insecticides, promote biodiversity, and enhance the sustainability of their cropping systems (Huss et al. 2022, Quintarelli et al. 2022, Scavo et al. 2022). Effective cultural control tactics for pest suppression would not only lower costs associated with purchasing and applying insecticides but also decrease the human health risks involved with the use of these chemical products (Huss et al. 2022). Such cultural practices could be combined with other integrated pest management tactics such as biological control and aphid-resistant soybean varieties, so that farmers can develop more robust sustainable pest management systems (Deguine et al. 2021, Philips et al. 2014, Riyaz and Kathiravan 2019).

This study demonstrates that relay-cropping soybean with a pennycress cover crop can significantly reduce soybean aphid populations compared with soybean grown without pennycress. However, across the site-years in this study, soybean aphid populations were low compared with the economic threshold of 250 aphids per plant (Ragsdale et al. 2007); therefore, further research is needed to evaluate the pest suppressive effects under higher levels of aphid infestation. In addition, future research should explore the long-term impacts of cover crops on pest dynamics and crop yields across a diverse agroecological region as well as the economic feasibility of such practices for farmers.

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