Agriculture Development Fund (ADF)
Project Final Report

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Project Title:	Intercropping pea with canola or oat: impact on nitrogen, disease and economics
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Abstract *(maximum 500 words)*

Detail an outline on overall project objectives, methods, key findings and conclusions for use in publications and in the ministry's database. The abstract should address the following (usually 1–2 sentences per topic):

- Key aspects of the literature review
- Problem under investigation or research question(s)
- Clearly stated hypothesis or hypotheses
- Methods used (including brief descriptions of the study design, sample, and sample size)
- Study results
- Conclusions

Compared to pea monocrop, intercropping with peas improves crop diversification and potentially delivers mutual benefits two both component crops. However, gaps exist in understanding nitrogen dynamics, soil health, disease impacts, and economic returns in pea-based intercropping systems on the Canadian prairies. This project is to evaluate the effects of pea-based intercrops (e.g., pea-oat and pea-canola) on grain yield, grain quality, N cycling, disease levels, and economic returns. We hypothesized that pea-based intercropping systems could enhance grain yield, N use efficiency, and economic returns; reduce disease occurrence; and improve soil quality.

A 3-year field study (2021-2024) was conducted in Melfort, Redvers, and Swift Current, SK. This study consisted of two 2-year phrases: Phase I (2021-2022) and phase II (2022-2023). Each phase consisted of intercrops in year 1 and wheat in year 2. The intercrop phase examined nine treatments: pea-oat intercrops with three N rates (0, ¼, and ½ recommended rate); pea-canola intercrops with three N rates (0, ¼, and ½ recommended rate); and monocrops of pea, oat, and canola. Grain yield, grain quality, water soluble carbon and nitrogen, soil mineral N, diseases, and economic returns were determined.

The land equivalent ratios of pea-canola and pea-oat were 0.98 and 0.94, respectively. No significant differences were observed in grain yield, protein-based yield, or energy-based yield between intercrops and monocrops. Application of N fertilizers had no effects on protein-based yield or energy-based yield of intercrops. Oats in pea-oat intercrops had a higher proportion of plump seeds (85%) compared to oat monocrop (79%). Incorporating peas with canola marginally increased canola oil content (46.0% in intercropping vs. 45.5% in monocropping). N application rates in intercrops had minimal effects on grain protein levels. The percentage of nitrogen derived from the atmosphere (%Ndfa) was higher in intercrop (42.8-64.9%) than in pea monocrop (40.5%), although lower biological nitrogen fixation was observed in intercrops due to the reduced pea biomass. Pea-oat fixed less N than pea-canola (19.5 vs 29.8 kg ha^{-1}) due to competitiveness of oat in pea-oat. Nitrogen transfer from pea to companion crops were low (2.2 to 6.3%). Pea-oat showed higher N fertilizer recovery rates compared to pea-canola (18.3% vs 15.2%). In the spring after the intercrop year, soil mineral nitrogen was not different between intercropping and monocropping. Additionally, water-soluble organic carbon (WEOC) and nitrogen (WEON) showed no significant differences between intercrop and monocrop or between the pea-oat and pea-canola systems. Pea-based intercropping had minimal impacts on pea diseases. Economically, monocrops had higher returns than intercrops, with canola monocrop resulting in the highest net income ($354 ha^{-1}). Pea-canola had higher economic returns (from $23 to $114 ha^{-1}) than pea-oat ($-10 to 39 ha^{-1}).

The findings indicated that intercrops might not be so profitable as monocrop but they increase the %Ndfa. Pea-oat intercrops improve plump seeds of oat and protein content of pea. Application of N fertilizer in intercrops provided no benefits in grain quality. Intercrops had limited benefits in soil water soluble carbon and nitrogen, diseases, and the following wheat crop.

Extension Messages *(3 to 5 bullet point in plain language)*

Provide key outcomes and their importance for producers/processors and the relevant industry sector.

1. N benefits of peas in intercrops were largely affected by the competitiveness of component crops. For example, the more competitive oat reduces the N benefits of peas, whereas the less competitive canola enhances them in pea-canola intercrops. Therefore, it is crucial to carefully adjust seeding rates of the component crops to maximize the advantages of intercropping
2. Pea-oat intercrops improve plump seeds of oats and protein content of peas
3. Intercrop might not be so profitable as monocrop
4. Pea-based intercrops did not show benefits in pea disease management and soil health improvement in this short-term study

Introduction *(maximum 1,500 words)*

Provide a brief project background and rationale.

Field pea has been successfully adapted to Saskatchewan, with an annual seeding area of over 1.2 million hectares since 2012 (Statistics Canada, 2023). Pea plays an important role in diversifying and stabilizing the dominant cereal-oilseed cropping systems in Saskatchewan (Liu et al., 2020, Knight, 2012). Most importantly, growing a pea crop substantially reduces the fertilizer N input for subsequent crops as a result of biological N_2-fixation during the pea phase (Liu et al., 2019b, Hossain et al., 2016, St. Luce et al., 2015). The yield benefits of growing pea for the following cereals and oilseeds are well documented (Liu et al., 2019a, Liu et al., 2020, O'Donovan et al., 2014, St. Luce et al., 2015, Lasisi and Liu, 2023). Pea is also widely used in intercropping to increase land productivity and improve crop quality (e.g., grain protein) compared to monocropping (Chapagain and Riseman, 2014, Strydhorst et al., 2008, Kontturi et al., 2011, Holzapfel and Chalmers, 2011). Intercropping pea with relatively rigid and upright crops, such as oat or canola, can minimize pea lodging (Kontturi et al., 2011, Shaw et al., 2020) while pea can provide N to intercropped oat or canola, creating mutual benefits between crops.

Mutual benefits of intercropping can lead to increased grain yield and quality compared to mono-cropping (Holzapfel and Chalmers, 2011, Strydhorst et al., 2008, Pelzer et al., 2012). In a study conducted in North Dakota, grain protein of oat increased by 1.8% in pea-oat intercrop compared with oat monocrop (Zwinger et al., 2018). Similarly, in a pea-oat intercrop demonstration trial in Saskatchewan, pea-oat intercrop showed potential to increase oat quality compared with oat monocrop (Shaw et al., 2020). May et al. (2004) found that fertilizer N rates were an important factor affecting oat quality indicators such as groat percentage, plump seed, and protein content. Holzapfel and Chalmers (2011) reported that applying fertilizer N did not benefit pea yield but had a positive effect on canola yield, to a certain extent in a pea-canola intercrop study. In addition, N application rates in pea-based intercrops affected not only the yield and quality of the non-legume crop, but also nodule formation, N fixation, and N transfer from pea to the non-legume crop (Chapagain and Riseman, 2014). Therefore, further studies are needed to determine the effects of N rates on grain yield and N transfer in pea-based intercrops.

Nitrogen transfer from pea to the non-legume crop during growing seasons can reduce fertilizer N application rates in intercrops. In a pea-barley intercrop, intercropped pea displayed increased nodulation (27–45%) and biological N_2 fixation (9–17%) compared with pea monocrop (Chapagain and Riseman, 2014). The enhanced N fixation by the intercropped pea likely increases N transfer from pea to the non-legume companion crop, thus improving N use efficiency and possibly grain quality. Oat is a mycorrhizal crop, while canola is a non-mycorrhizal crop. When pea is intercropped with oat or canola, the extent of N transfer from pea might be different because mycorrhizae play an essential role in N acquisition and transfer (He et al., 2009). To enhance N use efficiency and improve grain quality, it is important to quantify the difference in N transfer from pea to oat and from pea to canola.

In addition to well-known N benefits in pea-based intercrops, pea-based intercrops may increase carbon sequestration through greater plant biomass production and residue carbon returns. Chapagain and Riseman (2014) reported that pea-barley intercrops increased straw biomass carbon by 10% compared to barley monocrop. High biomass returns to soils from intercropping practices alter soil carbon and N pools, affecting soil health and the subsequent crop performance. However, most intercropping studies only assessed the intercropping year, without further exploring the “carry over” effects to the following crops. This carry-over function may affect soil N supply, crop yield, and grain quality (e.g., protein content) in the subsequent year of rotations. Knowledge of the carry-over effects of pea-based intercropping is required to better understand the role of intercropping at the cropping system level.

In addition to crop yield and soil health, intercropping may affect disease as a result of the alternation of host plants densities, soil biochemistry and/or micro-climates. Root rot can have a devastating impact on pea crops. This disease can be caused by a range of organisms, including Fusarium species and the oomycete *Aphanomyces euteiches* (Gossen et al., 2016*)*. Intercropping pea with oat may also influence Aphanomyces root rot severity in pea by means of oat root exudates that could potentially either induce germination of *A. eutieches* long-lived, tough oospores (Shang et al., 2000), making them more vulnerable, and/or directly kill oomycete zoospores (Deacon and Mitchell, 1985). Sclerotinia, caused by the fungus *Sclerotinia sclerotiorum*, can lead to significant damage in canola crops. Relative humidity is an important factor in the development of this disease (Derbyshire and Denton-Giles, 2016). It is possible that intercropping pea and canola could alter the humidity level in the crop canopy, thereby influencing disease. Blackleg, caused by the fungus *Leptosphaeria maculans*, is one of the most serious diseases of canola in western Canada. The impacts of pea-canola intercrops remain unknown for this disease. Thus, exploring how intercropping with pea impacts this disease has value. Economically, including pulse crops in wheat-canola cropping systems has the potential to increase profitability and enhance input use efficiencies (Khakbazan et al., 2018, Khakbazan et al., 2009). Fertilizer N, in combination with on-farm fuel use, can comprise over 80% of the total energy input in traditional production systems (Zentner et al., 2004). In addition, intercropping affects pesticide inputs, field operations, yield, grain separation, all of which affect economic returns. However, limited information is available on the economic evaluation of pea-oat or pea-canola intercrops at the whole farm level. With the growing popularity and importance of pea in Saskatchewan, it is important to evaluate the economic returns and risks of pea-based intercropping for a healthy cropping system.

In Saskatchewan, growers are interested in intercropping as a means of reducing fertilizer use in the cropping systems and increasing profitability. Therefore, we proposed and conducted a pea-based intercrop project to meet the grower's demands and adapt intercropping practices more efficiently.

Objectives and Progress *(add additional lines as needed)*

Please list the original objectives and/or revised objectives if ministry-approved revisions have been made to original objectives. A justification is needed for any deviation from original objectives.

Objective	**Progress** *(i.e., completed/in progress)*
(a) Determine effects of intercropping pea with oat or canola on grain yield, quality, and soil health	Completed
b) Quantify N transfer from pea to oat (mycorrhizal crop) or canola (non-mycorrhizal crop) and N recovery at different N rates	Completed
c) Assess effects of intercropping on disease	Completed
d) Evaluate economic returns of intercropping	Completed

Methodology *(maximum of five pages)*

Specify project activities undertaken during this reporting period. Include approaches, experimental design, tests, materials, sites, etc. Please note that any significant changes from the original work plan will require written approval from the ministry.

1. Experimental design

The study consisting of a 2-phases (i.e., phase I and II) was conducted at three sites in Saskatchewan: Swift Current, Melfort, and Redvers. Each phase of the study was a 2-year crop sequence, with Phase I covering 2021 and 2022, and phase II covering 2022 and 2023. In order to have a similar preceding crop background, both phases were established on a previous cereal crop. Two types of pea-based intercrops were evaluated: pea-oat and pea-canola, with oat representing a mycorrhizal crop and canola representing a non-mycorrhizal crop. Pea was regarded as the main crop while oat and canola were regarded as support crops. Consequently, pea in intercrop was seeded at two-third seeding rate used for pea monocrop, while oat (or canola) in the intercrop was seeded at one-half seeding rate used for oat (or canola) monocrop. That is, monocrops were seeded at a rate of 125, 300, and 200 seeds m^{-2} for pea, oat, and canola, respectively. The pea-oat and pea-canola intercrops were grown in mixed row arrangements, where pea was seeded at 2/3 its regular rate (85 seeds m^{-2}) and oat and canola were seeded at ½ their regular rate (150 and 100 seeds m^{-2}, respectively). The intercrops were arranged in mixed rows, since mixed-row intercropping resulted in higher yield than alternate-row intercropping (Holzapfel and Chalmers, 2011). In addition, three N rates were applied to each intercrop: no fertilizer N control, ¼ of recommended N rate for the non-legume monocrop, and ½ of recommended N rate for the non-legume monocrop. The treatment list is as follows:

- Pea + oat (0 N)
- Pea + oat (1/4 of recommended N rate for oat monocrop)
- Pea + oat (1/2 of recommended N rate for oat monocrop)
- Pea + canola (0 N)

- Pea + canola (1/4 of recommended N rate for canola monocrop)
- Pea + canola (1/2 of recommended N rate for canola monocrop)
- Pea monocrop
- Oat monocrop
- Canola monocrop

Fertilizer N rates for oat and canola monocrop were determined based on soil test recommendations. The N recommended rates for oat and canola were 50 and 81 kg N ha^{-1}, respectively at Swift Current and Redvers while the N recommended rates for oat and canola were 56 and 112 kg N ha^{-1}, respectively at Melfort. The pea monocrop received no synthetic N fertilizers. All site-year used urea, except for ^{15}N for studying N transfer in micro-plot. Along with the urea, monoammonium phosphate was seed placed at 40 kg ha^{-1} across all plots and 3.7 kg ha^{-1} of TagTeam granular inoculant was applied to treatments containing pea at the Swift Current and Redvers sites. In Melfort, pea was seed-treated with a liquid inoculant. The pea (both in monocrop and intercrop) was inoculated with commercial Rhizobium inoculants (e.g., TagTeam) that contained a phosphorus (P) solubilizing fungi *Penicillium bilaii* at seeding. The first year of each phase (i.e., 2021 for phase I and 2022 for phase II) was seeded to pea-based intercrops, pea monocrops, oat monocrops, canola monocrops as listed above. In the second year of each phase, all plots were seeded to wheat. A blanket N rate will be applied to wheat crop, based on soil test recommendations. In 2022, the N fertilizer rate for wheat were 84, 84 and 100 kg N ha^{-1} at Swift Current, Melfort, and Redvers, respectively.

After the crops were seeded, two 1 m x 1 m micro-plots were established in the centre of the plots with 2 m spacing between each other (**Figure 1**). The micro-plots enabled us to trace N through the system using the ^{15}N dilution method. One week after emergence, 0.3701 g m^{-2} of 50 atom% ^{15}N-enriched urea (equivalent to 5 kg N ha^{-1} at 18 atom% ^{15}N urea) was applied to the front ^{15}N micro-plot, while non-enriched urea was applied as a control to the back micro-plot. A steel frame was inserted into the soil, delineating the micro-plot area and the fertilizers were dissolved in 2 L of water before evenly applying them across the micro-plots. Additional 2 L of water was added to the micro-plots to leach the applied fertilizer into the rooting zone.

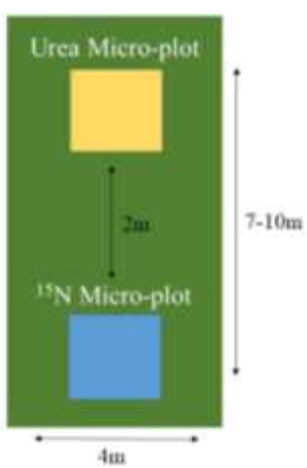

Figure 1. Plot design used at Swift Current and Melfort in 2021 and 2022 and at Redvers in 2021 to trace N using the ^{15}N dilution method.

2. Sample and data collection

2.1 Soil properties

Prior to establishing the experiment in the spring of 2021 for phase I and 2022 for phase II, two composite soil samples per block were collected at each site at 0-15 cm, 15-30 cm, and 30-60 cm. Soil was collected using a 28-mm diameter probe. The pH was determined using a saturated paste (McKeague, 1978), while bulk density soil samples were collected using a 49-mm diameter probe. Nitrate (NO_3^-) and ammonium (NH_4^+) were measured at AAFC-Swift Current to determine the total inorganic N in the soil sample, extracted with 2 M KCl. The samples were shaken for 15 minutes before being filtered through Whatman No. 40 filter paper and analyzed by a SEAL AutoAnalyzer 3 Continuous Segmented Flow Analyzer (Kitchener, Ontario, CA). The baseline soil properties are shown in **Table 1**.

Table 1. Physical and chemical soil characteristics of 0-15 cm soils from Swift Current, Melfort, and Redvers before seeding the intercrop phase in the spring of 2021 and 2022.

	2021			2022	
	Swift Current	Melfort	Redvers	Swift Current	Melfort
NH_4^+ (mg N kg^{-1})	3.3	11.8	4.7	3.2	6.6
NO_3^- (mg N kg^{-1})	4.1	11.2	10.4	2.7	6.8
PO_4^{-3} (mg P kg^{-1})	16.2	6.5	8.6	10.4	5.2
K (mg K kg^{-1})	266.3	223.0	157.0	299.5	277.9
Total N %	0.1	0.4	0.2	0.2	0.4
Organic C %	1.4	5.0	1.8	1.6	4.7
pH	7.1	6.7	7.6	7.3	6.0
EC (mS cm^{-1})	0.9	0.6	1.2	1.2	0.7
WEOC (µg g^{-1})	47.7	100.1	61.7	69.5	127.9
WEON (µg g^{-1})	6.5	13.3	9.1	7.5	15.2
Soil Texture	Loam	Clay	Sandy Clay Loam	Loam	Clay

EC, electronic conductivity. WEOC and WRON are Water extractable organic carbon and nitrogen, respectively.

Soil samples were collected the following spring from both micro-plots at 0-15 cm and 15-30 cm using a 17 mm diameter probe. Soil was air-dried, ground, and weighed between 15-35 mg (based on the N content in soil samples) using a Mettler Toledo balance XSR105 (Switzerland) that recorded weights to the nearest 1/100th of a milligram. Samples were placed in 8x5 mm tin capsules (Isomass Scientific Inc., Calgary, Canada), where they were compacted airtight and placed into 96-well trays (Thermo Fischer Scientific, Voltaweg 22, 2627 BC Delft, The Netherlands). These samples were analyzed for total percentage N and atom% ^{15}N content using a Flash 2000 Elemental Analyzer (Thermo Fisher Scientific, Voltaweg 22, 2627 BC Delft, The Netherlands), coupled with a Finnigan Delta V Plus Isotope Ratio Mass Spectrometer (Thermo Electron, Bremen, Germany) at AAFC-Lethbridge. The ^{15}N micro-plot showed the percentage of residual N in the soil that remained from the previous year's fertilizer application (%NREf) and samples collected from the control micro-plot demonstrated the N that was added to the soil by above-ground crop residue. However, due to negligible amounts of N added to the soil by above-ground crop residue, they were not analyzed.

2.2 Plant sampling and analysis

Once the plants reached physiological maturity, biomass samples were collected from the micro-plots and plots were harvested. Biomass samples were hand-harvested from the entirety of each micro-plot at ground level using clippers. Samples were separated by crop type, dried at 45ºC, threshed using a Wintersteiger combine, and small subsamples (~100 g) were taken for analysis. Straw was ground using a Wiley® Mill (Thomas Scientific, Swedesboro, NJ, United States) and the seed was ground using a laboratory mill (Perten Instruments, Shelton, CT, United States) and then both samples were finely ground using a ball mill (<0.5 mm) (Mixer Mill MM 500 Vario, Retsch USA Verder Scientific Inc., Newtown, PA, United States). They were placed in 8×5 mm tin capsules (Isomass Scientific Inc., Calgary, Canada), where they were compacted airtight and placed into 96-well trays (Thermo Fischer Scientific, Voltaweg 22, 2627 BC Delft, The Netherlands). These subsamples were weighed (4 mg) using a Mettler Toledo Balance XSR105 (Switzerland) that recorded weights to the nearest 1/100th of a milligram. These samples were analyzed for total percentage N and atom %^{15}N content using a Flash 2000 Elemental Analyzer (Thermo Fisher Scientific, Voltaweg 22, 2627 BC Delft, The Netherlands), coupled with a Finnigan Delta V Plus Isotope Ratio Mass Spectrometer (Thermo Electron, Bremen, Germany) at AAFC-Lethbridge.

Grain harvested from the intercrops was cleaned and separated based on crop type to determine crop yield. Canola yield was largely affected by grasshopper damage in Swift Current 2022; therefore, expected yields were calculated, taking into account the damage caused by grasshoppers. Five plants per plot were assessed for the percentage of pods eaten by grasshoppers to estimate each plot's yield loss and then expected yields were calculated. Yield was expressed at 10.0%, 13.5%, and 16.0% moisture for pea, oat, and canola, respectively. The land equivalent ratios (LER) were calculated based on **Eq. 1** to determine if the intercrops increased or decreased land use efficiency compared to the monocropping systems.

$$LER = LER_p + LER_o \quad \textbf{Eq.1}$$

$$\text{where } LER_p = \frac{Yield_{PeaPO}}{Yield_{PMono}} \text{ and } LER_o = \frac{Yield_{OatPO}}{Yield_{OMono}}$$

Oat was replaced with canola when calculating LER for the PC intercrop. This equation was also used to calculate Nitrogen LER (NLER), where yield was replaced with N uptake.

The %N in biomass samples was averaged between the two micro-plots. They were then used to calculate the N uptake of crops (**Eq. 2**), N harvest index (%NHI, **Eq. 3**), and N utilization efficiency (NutE, **Eq. 4**).

$$\text{N Uptake (kg ha}^{-1}) = (\%N_{Grain} \text{ x Grain Yield}) + (\%N_{Straw} \text{ x Straw Production}) \quad \textbf{Eq. 2}$$

$$\%NHI = \frac{\text{Grain N}}{\text{Above-ground dry matter N}} \text{ x } 100\% \quad \textbf{Eq. 3}$$

$$NUtE = \frac{\text{Grain Yield}}{\text{Above-ground dry matter N}} \quad \textbf{Eq. 4}$$

Then, the N inputs and N outputs were used to determine if N was added or removed from the field after harvest. Values above one represent N removals and values below one indicate N additions based on **Eq. 5**:

$$NUE_{crop} = \frac{\text{Grain N}}{\text{N Fertilizer + N Fixation + N Transfer}} \quad \textbf{Eq. 5}$$

The atom % ^{15}N content in plant samples enabled us to calculate the %Ndfa in pea (**Eq. 6**), the amount of N fixed by pea (**Eq. 7**), the percentage of atmospheric N transferred to companion crops (oat or canola) (**Eq. 8**), and the amount of N in the companion crop that came from N transfer (**Eq. 9**). Additionally, %NdfBNF was determined to observe the percentage of total N uptake in the intercrop (pea + oat/canola) that came from BNF (N fixation + N transfer) (**Eq. 10**). Furthermore, the percentage of N derived from the fertilizer (%Ndff) (**Eq. 11**) and derived from the soil (%Ndfs) (**Eq. 12**) were determined to observe where crops sourced majority of their N from.

$$\%Ndfa = \frac{^{15}\text{N atom \% excess}_{OMono} - {}^{15}\text{N atom \% excess}_{Pea}}{^{15}\text{N atom \% excess}_{OMono}} \text{ x } 100\% \quad \textbf{Eq. 6}$$

$$\text{N Fixation (kg ha}^{-1}) = (\%Ndfa_{Grain} \text{ x N Uptake}_{Grain}) + (\%Ndfa_{Straw} \text{ x N Uptake}_{Straw}) \quad \textbf{Eq. 7}$$

$$\%\text{N Transfer} = \frac{^{15}\text{N atom \% excess}_{OMono} - {}^{15}\text{N atom \% excess}_{OatPO}}{^{15}\text{N atom \% excess}_{OMono}} \text{ x } 100\% \quad \textbf{Eq. 8}$$

$$\text{N Transfer (kg ha}^{-1}) = (\%\text{N Transfer}_{Grain} \text{ x Oat N Uptake}_{Grain}) + (\%\text{N Transfer}_{Straw} \text{ x Oat N Uptake}_{Straw}) \quad \textbf{Eq. 9}$$

$$\%NdfBNF = \frac{\text{N Fixation + N Transfer}}{\text{Above-ground dry matter N}_{Pea} + \text{Above-ground dry matter N}_{Oat/Canola}} \text{ x } 100\% \quad \textbf{Eq. 10}$$

$$\%Ndff = \frac{^{15}\text{N atom \% excess in plant or soil}}{^{15}\text{N atom \% excess in fertilizer}} \text{ x } 100\% \quad \textbf{Eq. 11}$$

%Ndfs= 100 - %NdfBNF - %Ndff **Eq. 12**

where atom % ^{15}N excess is the ^{15}N in enriched plants minus the ^{15}N in non-enriched plants from the control micro-plot. The OMono was used as a reference crop and %Ndfa was calculated using the average of all OMono (at each site) to account for spatial variation across the field. For %N transfer, the oat monocrop and canola monocrop averages were used for their respective intercrops. All negative values were changed to 0 to show that no BNF or N transfer had occurred.

For %Ndff, the atom % ^{15}N excess in the soil was calculated as atom % ^{15}N content in the non-enriched soil subtracted from the atom % ^{15}N content of the enriched samples. Non-enriched soil samples were collected before the ^{15}N-enriched fertilizer application from the region between the micro-plots at 0-15 cm and 15-30 cm depths. Enriched soil was collected from both micro-plots at 0-15 cm and 15-30 cm the following spring.

Analysis of ^{15}N-enriched fertilizer recovery (%NREf) in the crops was determined for all treatments, but soil %NREf was only conducted on PO ½ N, PC ½ N, PMono, OMono, and CMono treatments at the Swift Current and Melfort sites using **Eq. 13**. Plant samples were evaluated at harvest and soil samples were evaluated the following spring.

$$\%NREf = \frac{\%Ndff \times \text{Above-ground dry matter N or Soil N}}{\text{N Fertilizer}} \times 100\%$$ **Eq. 13**

After harvest, the biomass samples (minus the subsample ~100g) collected from micro-plots were returned to the field approximately two months after harvest. This crop residue was chopped into 10 cm pieces to simulate going through a combine and returned to the opposing micro-plot. Hence, crop residue from the ^{15}N-enriched micro-plot was placed on the non-enriched micro-plot and vice versa. This straw swap methodology was taken from Taveira et al. (2020), and straw was held in place throughout the winter by a 2-5 cm wire mesh net anchored to the ground by modified fencing staples.

2.3 Weather data collection

Weather data for each site-year were gathered from either on-site or nearby official weather stations. **Table 2** displays the precipitation and air temperature for the growing seasons, along with long-term average values.

Table 2. Precipitation and mean daily temperature at Swift Current, Melfort and Redvers: 2021, 2022, 2023 and long-term norms.

	Precipitation (mm)				Mean Temperature (°C)			
	2021	2022	2023	Long-term	2021	2022	2023	Long-term
				Swift Current				
May	35.9	51.2	41.0	51.2	9.5	10.9	14.8	10.9
June	29.6	37.7	32.9	77.1	18.4	15.9	17.7	15.3
July	38.9	90.4	63.3	60.1	21.7	19.8	18.4	18.2
August	55.7	7.5	42.1	47.4	18.0	20.9	18.8	17.6
Total	160.1	186.8	179.3	235.8	67.6	67.5	69.7	62.0
Difference	-75.7	-49	-56.5		5.6	5.5	7.7	
				Melfort				
May	31.4	90.8	31.5	42.9	9.6	9.9	13.8	10.7
June	37.6	78.1	26.4	54.3	18.2	15.2	19.2	15.9
July	0.2	34.9	16.4	76.7	20.1	18.2	16.9	17.5
August	69.3	36.5	50.0	52.4	16.9	18.7	17.3	16.8
Total	138.5	240.3	124.3	226.3	64.8	62	67.2	60.9
Difference	-87.8	14	-102		3.9	1.1	6.3	

				Redvers				
May	41.4	121.0	84.1	60.0	10.0	10.2	14.5	11.1
June	95.2	75.0	33.0	95.2	18.7	16.3	19.7	16.2
July	38.4	259	10.8	65.5	20.8	19.2	17.6	18.7
August	72.1	25.2	37.6	46.6	17.5	18.9	17.8	18.0
Total	247.1	480.2	165.5	267.3	67	64.6	69.6	64.0
Difference	-20.2	212.9	-101.8		3.0	0.6	5.6	

Long-term indicates the period from 1981 to 2010.

2.4 Grain yield and quality

Crop growth stages (e.g., emergence, flowering, and physiological maturity dates) were recorded. Plant lodging was rated on a scale of 1 (upright) to 10 (flat). Crops were harvested using a plot combine. The grains from intercrops were cleaned and separated, then the land equivalent ratio (LER) was calculated and used to assess yield performance of intercrops based on **Eq. 14**:

$$\mathrm{LER} = \frac{\mathrm{W_{intercrop\ A}}}{\mathrm{W_{monocrop\ A}}} + \frac{\mathrm{W_{intercrop\ B}}}{\mathrm{W_{monocrop\ B}}} \quad \textbf{Eq. 14}$$

Where $W_{intercrop\ A}$ is the yield of crop A in the A-B intercropping, $W_{intercrop\ B}$ is the yield of crop B in the A-B intercropping, $W_{monocrop\ A}$ is the yield of A in the monocropping, and $W_{monocrop\ B}$ is the yield of B in the monocropping.

For grain quality, all grains were analyzed for total carbon and N content at Swift Current Centre. Oat milling quality (e.g., % plump kernels, β-glucan content, and protein content) was analyzed at General Mills laboratory through in-kind support to this project.

To evaluate the yield productivity of various cropping systems, including intercrops and monocrops, we employed measures of protein-based yield (PBY), which reflects the robustness of grain nitrogen removal, and energy-based yield (EBY), an indicator of grain carbon storage capacity. These yields were calculated on a plot basis according to **Eq. 15** (**Eq. 15.1** for oat and pea crops, and **Eq. 15.2** for canola crops) and Equation 16.

$$\mathrm{PBY_{oat/pea}} = \text{Grain yield } \times \text{Grain N concentration } \times 6.25 \quad \textbf{Eq. 15.1}$$

$$\mathrm{PBY_{canola}} = \text{Grain yield } \times \text{Protein concentration} \quad \textbf{Eq. 15.1}$$

$$\mathrm{EBY} = \text{ Grain yield } \times \text{Caloric content} \quad \textbf{Eq. 16}$$

The Caloric contents of oat, canola, and pea are 3,890, 8,840, and 3,410 kcal kg^{-1}, respectively.

2.5 Disease assessment

The severity of mycosphaerella blight of pea was rated at early flowering on a 0-5 scale shown in **Table 3** using five randomly selected plants in each plot. Root rot of pea was assessed on 5 randomly selected plants per plot at early flowering stage. Root rot severity was scored on a 0-5 scale (Willsey, Chatterton, et al., 2018) (**Table 4**).

Table 3. Rating scale (0-5) for assessment of Ascochyta / Mycosphaerella blight on peas.

Rating	Description
0	No visible necrosis on leaf and/or stem

1	Under 5% of plant area covered by necrosis. A few flecks on leaves and a few streaks on stems
2	5-25% of plant area covered by necrosis. Numerous flecks on leaves and streaks on stems
3	25 to 50% of plant area covered by necrosis, with coalescent streaks forming 3- to 5-mm lesions on stems
4	50 to 75% of plant area covered by necrosis, with a necrotic zone up to 3 mm wide encircling the stem
5	More than 75% of plant area covered by necrosis, necrotic zone wider than 3 mm encircling the stem

Table 4. Pea root rot scale (0-5).

Rating	Description
0	Healthy, no disease
1	1-25% of root area discolored
2	26-50% of root area discolored
3	51-75% of root area discolored
4	76-100% of root area discolored
5	Plant dead

Sclerotinia and blackleg of canola were both assessed at maturity with 50 plants, 10 plants were selected from each of five randomly selected locations in each plot. The blackleg and Sclerotinia rating scales are summarized in **Table 5** and **Table 6**. Oat was assessed for crown rust and leaf spot or blotch diseases based on 10 or 20 flag leaves per plot at the late milk stage. Crown rust was rated on a 0-100 scale, based on percent area impacted. Leaf spot or blotch was scores on 0-11 scale.

Table 5. Rating of blackleg of canola.

Rating	Description
0	No disease visible in the cross section
1	Diseased tissue occupies up to 25% cross-section
2	Diseased tissue occupies 26 to 50% cross-section
3	Diseased tissue occupies 51 to 75% cross-section
4	Diseased tissue occupies > 75% cross-section with little constriction of affected tissues
5	Diseased tissue occupies 100% cross-section with significant constriction; tissue dried and plant dead

Table 6. Rating of Sclerotinia of canola

Rating	Description
0	No symptoms of disease on plant
1	A few pods affected
2	One major branch girdled; ¼ of the plant affected
3	Two major branches girdled; ½ of the plant affected
4	Three or more major branches girdled; ¾ of the plant affected
5	Main stem lesion affecting entire plant

2.6 Economic assessment

For economic analysis, a 12-yr average (2012-2023) input (i.e., seed and fertilizers) costs and output (i.e., grains) prices were used to quantify total production cost, gross revenue and net revenue for the intercrops and monocrops. The cost of plant protection was calculated based on pesticide unit price in 2021. Fixed costs along with other field operational (i.e., seeding, fertilizer and herbicide applications, harvesting) costs were determined using an average of each operational price from Saskatchewan Crop Planning Guide 2021 and 2022. The cost of grain separation to individual crops from intercrops was calculated based on seed cleaning price obtained from personal communication with Hickseed Ltd. (https://hickseeds.com).

2.7 Data analysis

Data were statistically analyzed using R Studio (R Core Team, 2021; Wickham, 2016; Wickham & Girlich, 2022). To compare intercrops to their respective monocrops, a mixed linear effect model (Kuznetsova, Brockhoff, & Christensen, 2017) was used with treatment as a fixed factor and site, year, and replicate as random factors. Sites were combined for the analyses to create a robust dataset that incorporated sites across Saskatchewan. Two analyses were conducted, one for pea-oat intercrops and their respective monocrops and another for pea-canola intercrops and their respective monocrops. Differences of least mean squares (Kuznetsova et al., 2017) were used to determine treatment differences. A two-way factorial analysis, using a mixed linear effect model, was also conducted to determine differences between intercrops and N fertilizer rates. Differences of least mean squares (Kuznetsova et al., 2017) were used to determine treatment differences in the factorial.

For ^{15}N-enriched fertilizer recovery, all five treatments were analyzed together using a mixed linear effect model, with treatment as a fixed factor and site, year, and replicate as random factors. The *p*-values ≤0.05 were considered significant. Data points further than three standard deviations from the mean were considered outliers and removed from the dataset. The normality of the residuals was tested using the Shapiro-Wilk statistic and the homogeneity of variance was tested visually using fitted vs. residual plots. Log transformations were conducted where necessary but back-transformed for presentation.

Data on net returns were analyzed each site and each year separately and across years, and also across locations and years using Mixed procedure with 'nlme' R statistical package. Treatment means were compared with least square means using 'lsmeans' and 'multcompview' R packages when F-test was significant ($p<0.05$).

Results and Discussions *(maximum of 30 pages (not including figures or tables))*

Describe research accomplishments during the reporting period under relevant objectives listed under "Objectives and Progress" section. Please accompany a written description of results with tables, graphs and/or other illustrations. Provide discussion necessary to the full understanding of the results. Where applicable, results should be discussed in the context of existing knowledge and relevant literature. Detail any major concerns or project setbacks.

1. Grain yield

In the comparison of intercrop versus monocrop systems, they has comparable grain yield, protein-based yield, and energy-based yield (**Table 7**). Within intercrops, the PO (pea-oat) had a higher grain yield of 2694 kg ha^{-1}, which is 16.8% higher than PC (pea-canola). PO's protein-based yield was lower by 8.7% compared to PC, and its energy-based yield was significantly higher by 33.3%. The application of N fertilizer did not significantly affect the yield of intercrops receiving different among of N fertilizers.

When considering intercrop and fertilization interaction, the PO1/2N treatment yielded the most at 2822 kg ha^{-1}, which is a 7.1% increase over PO0N. The protein-based yield for PO1/2N saw an increase of 2.4% over PO0N, and the energy-based yield matched the highest recorded yield in intercrops at 53.3 GJ ha^{-1}, shared with PO1/4N. Conversely, PC intercrops with added 1/2N (PC1/2N) had the lowest yield at 1861 kg ha^{-1}, a significant decrease of 10.6% from PC0N, while its energy-based yield decreased by 24.7% from PC0N.

Comparing monocrops, PMono had the highest protein-based yield at 521 kg ha^{-1}, substantially outperforming OMono and CMono by 29.0% and 18.4%, respectively. However, OMono had the highest energy-based yield at 60 GJ ha^{-1}, which is significantly higher than PMono and CMono by 100% and 33.6%, respectively. Lastly, CMono had the lowest grain yield of 1702 kg ha^{-1}, a decrease of 20.5% from PMono and 43.6% from OMono.

Table 7. Productivity of grain yield (kg ha^{-1}), protein-based yield (kg protein ha^{-1}) and energy-based yield (GJ ha^{-1}) of pea-oat and pea-canola intercrops compared to their respective monocrops of pea, oat, and canola at different N rate supplied.

		Grain yield	Protein-based yield	Energy-based yield
Intercrop[1] vs monocrop	Intercrop	2338	456	44.4
	Monocrop	2286	455	45.0
Intercrop	PO	2694a	429b	53.3a
	PC	2163b	470a	40.0b
Fertilization	0N	2378	465	42.9
	1/4N	2293	458	44.8
	1/2N	2342	445	45.5
Intercrop × Fertilization	PO0N	2674b	421b	50.6a
	PO1/4N	2558b	426b	53.3a
	PO1/2N	2822a	431b	53.3a
	PC0N	2081c	509a	35.2b
	PC1/4N	2028c	489a	37.7b
	PC1/2N	1861c	459ab	36.3b
Monocrops	PMono	2142b	521a	30.0c
	OMono	3015a	404b	60.0a
	CMono	1702c	440b	44.9b

[1]Intercrop includes pea-oat and pea-canola at 0, ¼, and ½ N input. PO is the averaged value of pea-oat at 0, ¼, and ½ N input, while PC is the average of pea-canola cropping at 0, ¼, and ½ N input. PMono, Omono, and CMono are pea, oat, and canola monocrop. Different letters in each column of comparison indicate significant differences at α = 0.05.

No differences in grain LER were observed between these intercrops and neither intercrop provided a yield advantage over their monocropping systems (**Figure 2A**). However, grain LER demonstrated that pea-oat (0.94) and pea-canola (0.98) were comparable to monocrop yields. That is, in site-specific analyses, Melfort demonstrated that intercrops could produce up to 10% (pea-oat) and 13% (pea-canola) yield advantages, while Redvers was comparable to monocrops, and intercrops in Swift Current reduced grain yields. Within the intercrops, opposing crop types (legume or non-legume) contributed the majority of yield. In pea-oat, oat was the dominant crop (LERo=0.65), but in pea-canola, pea was the dominant crop (LERp=0.64). Fertilizer rate did not affect grain LER.

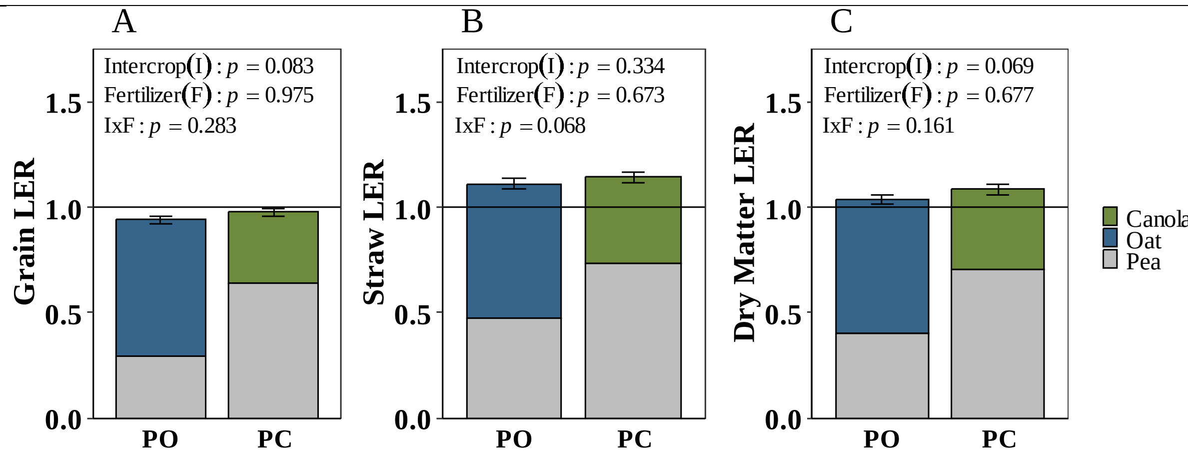

Figure 2. Land equivalent ratios (LER) for grain yield (A), straw biomass (B), and above-ground dry matter (C) produced by pea-oat (PO) and pea-canola (PC) intercrops. Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea which received no N fertilizer. Results are the combined analysis of five sites. Bars are means with standard errors (n=60) and p≤0.05 were considered significant. LER values ≥1 indicate an intercrop advantage, whereas, values ≤1 show an intercrop disadvantage.

2. Grain quality

2.1 Oat quality

Oat crops integrated with other plants had a higher plumpness percentage yet yielded lower in terms of plump, protein, groat, and β-glucan compared to monocrops. The overall yield difference between the intercrop and monocrop systems, rather than the individual concentration levels of these components, accounts for these results (**Table 8**). Specifically, intercrop systems achieved a higher plump percentage (85.4%) compared to Monocrop systems (78.9%), yet monocrop systems had a significantly greater plump yield of 2431 kg ha^{-1} compared to 1738 kg ha^{-1} in Intercrop systems. While protein content was higher in monocrop systems at 17.5% resulting in a higher protein yield (520 kg protein ha^{-1} based on the NIR analysis), both systems recorded the same groat content. However, monocrop groat yield surpassed intercrop with 18.8 against 12.6 kg ha^{-1}. For β-glucan content and yield, monocrop systems slightly outperformed intercrop, 4.7% and 141 kg ha^{-1}, respectively, compared to 4.6% and 94 kg ha^{-1} in intercrop.

Table 8. The impact of various cropping systems on oat quality, focusing on characteristics such as plumpness, protein content, groat levels, and β-glucan concentrations, along with the corresponding yields. The labels 1/4N, 1/2N, and 0N represent pea-oat intercrops with ¼, ½, and 0 N application rates for oat crops, respectively. Mono refers to the oat monocrop, while the intercrop includes pea-oat system at 0N, 1/4N, and 1/2N input. Significant differences between treatments within a subplot are denoted by differing letters.

		Plump percentage	Plump yield	Protein	Protein yield	Groat	Groat yield	β-glucan	β-glucan yield
Inter. vs mono.	**Inter.**	85.4a	1738b	16.5	329b	0.62	12.6b	4.6	94b
	Mono.	78.9b	2431a	17.5	520a	0.62	18.8a	4.7	141a
Fertilization	**0N**	86.1	1675b	16.3	313	0.61	11.9	4.6	91
	1/4N	85.3	1693b	16.5	322	0.63	12.3	4.6	92
	1/2N	84.8	1846a	16.7	352	0.62	13.6	4.6	99

2.2 Canola quality

The monocrop system outperformed the intercrop in both oil and protein yields for canola, with 559 kg oil ha^{-1} compared to 236 kg oil ha^{-1} and 299 kg protein ha^{-1} compared to 116 kg protein ha^{-1}, respectively (**Table 9**). Despite this, oil content was slightly higher in the intercrop system at 46.0 versus 45.5 kg oil ha^{-1} in monocrops. Fertilization influenced yields positively; without N, the oil and protein yields were lowest at 197 kg oil ha^{-1} and 97 kg protein ha^{-1}. As N application increased, there was a corresponding increase in yield, peaking at 339 kg ha^{-1} for oil and 169 kg ha^{-1} for protein with 1/2N, showing a clear trend of rising yields with increased N levels.

Table 9. The impact of various cropping systems on canola oil and protein yielding. The labels Pc1/4N, Pc1/2N, and Pc0N represent pea-canola intercrops with ¼, ½, and 0 application rates for canola crops, respectively. Cmono refers to the canola monocrop. Significant differences between treatments within a subplot are denoted by differing letters.

		Oil	Oil yield	Protein	Protein yield
Intercrop vs monocrop	**Intercrop**	46.0	236b	23.7	116b
	Monocrop	45.5	559a	24.9	299a
Fertilization	**0N**	45.9	197c	23.6	97c
	1/4N	46.1	274b	23.9	136b
	1/2N	45.8	339a	24.2	169a

3. Biomass

Like grain yield, pea monocrop produced more pea straw and oat monocrop produced more oat straw than all of the pea-oat intercrops (**Table 10**). Nevertheless, the total straw produced by pea-oat intercrops was similar to that produced by pea monocrop, The one exception was straw produced by pea-oat at ½ N, which was 21% higher than pea monocrop. Similarly, total straw produced by pea-oat at ¼ N and at ½ N was 14% and 23% higher than oat monocrop, respectively, while pea-oat 0 N was comparable to oat monocrop. In pea-canola intercrops, pea straw decreased with increasing fertilizer rate and canola straw increased, similar to trends observed for grain yield. However, pea monocrop and canola monocrop produced the most pea and canola straw, respectively, compared to the intercrops. No differences between treatments were observed for total straw production.

Pea intercropped with canola produced 55% more straw than pea intercropped with oat (**Table 11**). Interactions caused pea-canola at 0 N and at ¼ N treatments to produce the most pea straw, where pea-canola 0 N was, on average, 76% higher than the pea-oat intercrops and pea-canola ¼ N was, on average, 64% higher than the pea-oat intercrops. However, no differences were observed for total straw production. This translated into no straw LER differences between intercrops; however, both intercrops produced more straw than their respective monocrops (**Figure 2B**). The pea-oat intercrop increased straw production by 11% and pea-canola produced 14% more straw than their monocrops. Within the intercrops, oat again was dominant in pea-oat (LERo=0.64) and pea was dominant in pea-canola (LERp=0.74) (**Figure 2B**), similar to what was observed for grain yield.

The total above-ground biomass produced by pea-oat intercrops was, on average, 18% larger than pea monocrop and equivalent to oat monocrop (**Table 10**). Conversely, no differences were observed between pea-canola intercrops and its monocrops for biomass production. Between intercrops, an interaction enabled pea-oat ½ N to produce the largest biomass, larger than all pea-canola intercrops (**Table 11**). The pea-canola ½ N had the smallest biomass production and was, on average, 16% smaller than all three pea-oat intercrops. Using LER, no differences were observed between intercrops, but pea-oat and pea-canola intercrops increased biomass by 4% and 8% compared to their respective monocrops (**Figure 2C**). Again, oat was the dominant crop in pea-oat (LERo=0.64) and pea was the dominant crop in pea-canola (LERp=0.71).

Table 10. Straw and biomass (kg ha^{-1}) of pea-oat and pea-canola intercrops compared to their respective monocrops of pea, oat, and canola.

	Straw

	Pea	Oat/Canola	Total	Total biomass
Pea-oat (PO) vs. monocrop				
PO 0 N	1472 b	1984 b	3430 abc	6075 a
PO ¼ N	1579 b	2006 b	3585 ab	6036 a
PO ½ N	1713 b	2170 b	3883 a	6705 a
PMono	3200 a	No data	3200 bc	5317 b
OMono	No data	3152 a	3152 c	6252 a
Pea-canola (PC) vs. monocrop				
PC 0 N	2794 b	999 c	3793	5874
PC ¼ N	2604 b	1486 b	3826	5753
PC ½ N	1971 c	1639 b	3591	5417
PMono	3200 a	No data	3200	5317
CMono	No data	3613 a	3613	5390

Table 11. Comparison of pea-oat (PO) and pea-canola (PC) intercrops' biomass productivity (kg ha^{-1}).

		Straw		Total biomass
		Pea	Total	
Intercrop	PO	1590 b	3636	6283 a
	PC	2462 a	3736	5683 b
Fertilizer Rate	0 N	2150 a	3616	5969
	¼ N	2078 a	3699	5898
	½ N	1838 b	3741	6078
Intercrop × Fertilizer Rate	PO 0 N	1472 c	3430	6075 ab
	PO ¼ N	1579 c	3585	6036 b
	PO ½ N	1713 c	3883	6705 a
	PC 0 N	2794 a	3793	5874 bc
	PC ¼ N	2604 a	3826	5753 bc
	PC ½ N	1971 b	3591	5417 c
***P*-values**				
Intercrop (I)		**<0.001**	0.183	**<0.001**
Fertilizer Rate (F)		**0.032**	0.588	0.972
I x F		**0.005**	0.078	**0.017**

4. Biological nitrogen fixation

Observing the BNF capabilities of pea grown in PO intercrops, all three PO intercrops had larger %Ndfa than PMono, with the largest %Ndfa being produced by the PO 0 N and PO ¼ N treatments (**Table 12**). Between sites, Melfort 2021 experienced limited N fixation, which reduced overall %Ndfa and revealed no differences between treatments. Similarly, when pea was intercropped with canola, PC 0 N and PC ¼ N produced %Ndfa larger than PMono. Within the PC intercrop, %Ndfa generally decreased with increasing fertilizer rate.

Table 12. Nitrogen derived from the atmosphere (%Ndfa) and N fixation by pea in pea-oat (PO) intercrops, pea-canola (PC) intercrops, and pea monocrop (PMono). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended) and PMono received no N fertilizer. Results are the combined analysis of five sites.

	%Ndfa		**N Fixation (kg N ha^{-1})**	
	Grain	**DM[1]**	**Grain**	**DM**
		Pea-oat vs. monocrop		
PO 0 N	61.6 ab	49.6 ab	20.5 b	29.3 b
PO ¼ N	64.9 a	55.2 a	21.8 b	32.8 b
PO ½ N	54.3 b	44.8 b	16.4 b	24.3 b
PMono	40.5 c	32.7 c	35.6 a	39.1 a
		Pea-canola vs. monocrop		
PC 0 N	53.2 a	42.8 a	37.3 a	50.2 a
PC ¼ N	51.2 a	38.4 a	31.5 a	41.3 ab
PC ½ N	42.8 b	37.1 ab	20.8 b	30.4 c
PMono	40.5 b	32.7 b	35.6 a	39.1 b

[1] DM= above-ground dry matter. Means followed by the same letter are not significantly different (p>0.05).

The large %Ndfa of PO was evident in comparison to PC and proved to be 24% (grain) and 34% (DM) higher than PC (**Table 13**). Fertilizer rates also impacted grain %Ndfa, where 0 N and ¼ N had larger %Ndfa than ½ N, but DM %Ndfa was unaffected by fertilizer rate. In contrast to %Ndfa, the N fixed by PO intercrops was lower than PMono for grain and DM (**Table 12**). Nitrogen fixation was positively correlated with pea DM (**Figure 3**); therefore, the large pea DM produced by PMono, in comparison to the PO intercrops, influenced N fixation. Nonetheless, PC intercrops produced comparable amounts of N fixation to PMono when they received 0 N and ¼ N rates (**Table 12**). The PC 0 N DM even fixed 28% more N than PMono. Conversely, PC ½ N reduced grain N fixation by 71% and DM N fixation by 29% compared to PMono.

The reduced pea biomass of PO, compared to PC (**Table 11**), lowered PO grain and DM N fixation compared to PC (**Table 13**). The large amounts of N fixed by PC were influenced by N fertilizer rate, where PC 0 N and PC ¼ N fixed the most N of all intercrop treatments within the grain and DM of pea plants. Partial NLER (NLERp) of N fixed by pea was used to compare intercrops and monocrops. The large N fixation of PC was evident in NLERp, where PC was 53% higher than PO (**Table 13**). However, neither intercrop provided an N fixation advantage over PMono (value above one). That being said, the intercropped pea was seeded at 2/3 the rate of PMono; thus, NLERp was compared to 0.67 to determine if intercrops provided an N fixation advantage on a per-plant basis. Based on this, PC increased N fixation by 23% over PMono. Nonetheless, PO showed an 8% disadvantage compared to PMono, even when considering the reduced pea seeding rate.

Table 13. Biological N fixation and N transfer in pea-oat (PO) and pea-canola (PC) intercrops. Intercrops received three N fertilizer rates (0, ¼, ½ of N recommended). Results are the combined analysis of five sites.

		%Ndfa[1]		**N Fixation (kg N ha^{-1})**			**%N Transfer**	
		Grain	DM_a[2]	Grain	DM	$NLER_p$[3]	Grain	DM
Intercrop	PO	60.2 a[4]	49.8 a	19.5 b	28.7 b	0.59 b	2.2	2.5
(n=60)	PC	49.0 b	39.5 b	29.8 a	41.0 a	0.90 a	6.3	4.4
Fertilizer Rate	0 N	57.3 a	46.1	29.2 a	40.3 a	0.85 a	3.8	3.3
(n=40)	¼ N	58.1 a	47.1	26.6 a	37.0 a	0.79 a	4.9	3.5
	½ N	48.6 b	40.9	18.6 b	27.2 b	0.59 b	4.1	3.5
Intercrop x	PO 0 N	61.6	49.6	20.5 b	29.3 b	0.66	2.3	2.3
Fertilizer Rate	PO ¼ N	64.9	55.2	21.8 b	32.8 b	0.63	3.1	3.6
(n=20)	PO ½ N	54.3	44.8	16.4 b	24.3 b	0.49	1.2	1.7
	PC 0 N	53.2	42.8	37.3 a	50.2 a	1.04	5.3	4.3
	PC ¼ N	51.2	38.4	31.5 a	41.3 a	0.95	6.6	3.3

PC ½ N	42.8	37.1	20.8 b	30.4 b	0.69	7.0	5.4
***P*-values**							
Intercrop (I)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	ns[4]	ns
Fertilizer Rate (F)	**0.002**	0.077	**<0.001**	**<0.001**	**<0.001**	ns	ns
I x F	0.812	0.356	**0.010**	**0.034**	0.208	ns	ns

[1] %Ndfa= percentage of N derived from the atmosphere. [2] DM= above-ground dry matter. [3] $NLER_p$ values ≥1 indicate an intercrop advantage, whereas, values ≤1 show an intercrop disadvantage. [4] Means followed by the same letter are not significantly different (*p*>0.05).

Minimal amounts of the N fixed by pea were transferred to companion crops (oat or canola). No statistical analysis was conducted for N transfer because of the extreme variability in the dataset. Many values measured no N transfer between crops, but a few site years determined that N transfer was possible. Redvers 2021 demonstrated the largest %N transfer, where PC (22%) was larger than PO (7%). This influenced the site combined analysis, where although not statistically different, PC appeared to benefit more from N transfer than PO in both grain and DM (**Table 13**).

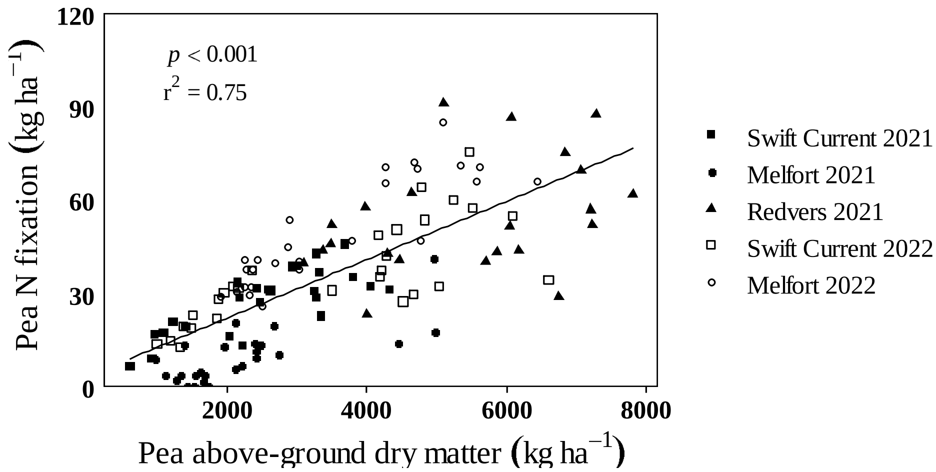

Figure 3. N fixed by pea in relation to above-ground pea dry matter production (n=140).

5. Nitrogen fertilizer recovery

The %NREf was determined to observe the percentage of applied fertilizer utilized by the crop. The PO ½ N recovered the largest percentage of 15N fertilizer, increasing %NREf by 17% and 23% compared to PO ¼ N and PMono, respectively (**Figure 4A**). The PC intercrops showed no difference in %NREf compared to their monocrops (**Figure 4B**); however, PC did have 20% lower %NREf than PO. In the PO intercrop, oat recovered on average 14% of the fertilizer applied and pea recovered 5%. In the PC intercrop, pea recovered the most fertilizer with an average of 10% and canola recovered an average of 6%. This followed a similar pattern to productivity and N accumulation, where oat was PO's dominant crop and pea was PC's dominant crop. Fertilizer rate did not impact the %NREf of intercrops (**Figure 5**).

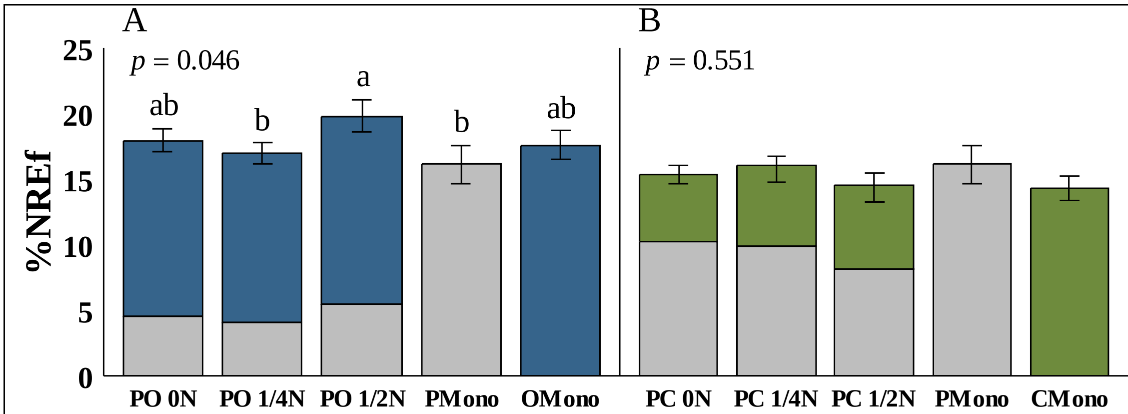

Figure 4. Nitrogen recovery rate of 15N-enriched urea fertilizer (%NREf) by pea-oat (PO) (A) and pea-canola (PC) (B) intercrops compared to their respective monocrops (PMono, OMono, CMono). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea, which received no N fertilizer. Different letters show significant differences between treatments. Results are the combined analysis of five sites. P≤0.05 were considered significant and bars are means with standard errors (n=20).

Secondly, total %NREf was determined, considering fertilizer that was utilized by the crop and what remained in the soil. This was only measured for intercrops that received the ½ N rate and the monocrops; therefore, only five treatments are shown in **Figure 6**. The PO ½ N and OMono were able to recover the most fertilizer, where PO ½ N recovered 34%, 26%, and 33% more fertilizer than PC ½ N, PMono, and CMono, respectively. On average, crops recovered 15% of the 15N fertilizer and 23% remained in the soil, for a total of 38% fertilizer recovered and 62% lost to the environment. No differences between treatments were seen for soil or total %NREf.

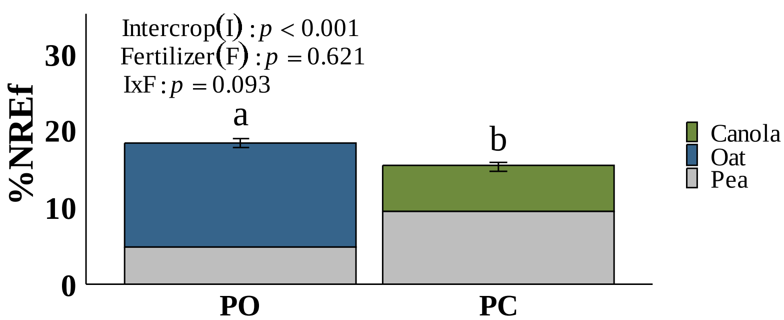

Figure 5. Nitrogen recovery rate of 15N-enriched urea fertilizer (%NREf) by pea-oat (PO) and pea-canola (PC) intercrops. Intercrops received three N fertilizer rates (0, ¼, ½ of recommended). Different letters show significant differences between treatments. Results are the combined analysis of five sites. P≤0.05 were considered significant and bars are means with standard errors (n=60).

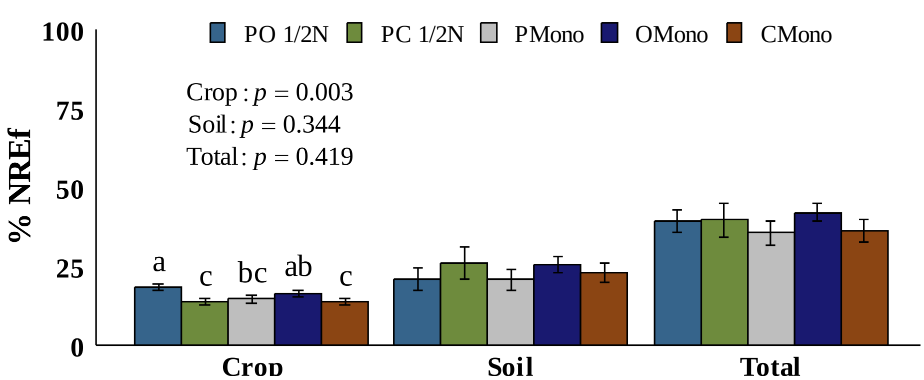

Figure 6. Nitrogen recovery rate of 15N-enriched fertilizer urea (%NREf) by the crop and soil of pea-oat (PO) and pea-canola (PC) intercrops compared to their respective monocrops (PMono, OMono, CMono). Intercrops received ½ of their recommended N fertilizer rate; monocrops received their full N recommendation, except pea, which received no N fertilizer. Different letters show significant differences between treatments for the different sources of N recovery. Results are the combined analysis of four sites. P≤0.05 were considered significant and bars are means with standard errors (n=16).

6. Nitrogen use efficiency

Several NUE indices were determined, including the percentage of N uptake partitioned to grain (%NHI), the yield produced per unit of plant N (NUtE), and N that was added/removed from the field after harvest (NUEcrop). Based on the N taken up by pea, PMono partitioned more N to grain than PO intercrops. (**Table 14**). Pea %NHI generally decreased as PO intercrops received more N fertilizer, with PMono having NHI 33% higher than PO ½ N. No differences were observed between PO intercrops and OMono for oat %NHI. The pea NUtE was similar to pea %NHI, which generally decreased as PO intercrops received more N fertilizer (**Table 14**). That being said, the intercrops produced, on average, 32% less yield per unit of DMNa than PMono. In contrast, the three intercrops produced larger oat NUtE than OMono. On average, the intercrop produced 14% more oat yield than OMono, per unit of DMNa.

Table 14. Nitrogen use efficiency indicators of pea-oat (PO) and pea-canola (PC) intercrops compared to their respective monocrops (PMono, OMono, CMono). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea, which received no N fertilizer. Results are the combined analysis of five sites.

	% NHI[1]		**NUtE**[2]		**NUE$_{crop}$**[3]
	Pea	**Oat/Canola**	**Pea**	**Oat/Canola**	
			Pea-Oat		
PO 0 N	61.8 b[4]	76.5	14.5 b	39.3 a	2.2 a
PO ¼ N	58.5 bc	75.1	13.9 bc	38.2 a	1.6 b
PO ½ N	54.5 c	77.1	12.8 c	38.6 a	1.3 c
PMono	72.5 a	nd	18.2 a	nd	2.0 a
OMono	nd[5]	75	nd	33.9 b	1.2 c
			Pea-Canola		
PC 0 N	69.5 b	70.0 b	17.1 b	18	1.7 a
PC ¼ N	66.1 c	70.6 b	16.7 b	17.7	1.2 b
PC ½ N	66.2 c	75.2 a	16.8 b	18.9	0.9 c
PMono	72.5 a	nd	18.2 a	nd	2.0 a
CMono	nd	76.0 a	nd	17.8	0.8 c

[1] N harvest index (NHI)= grain N/above-ground dry matter N x 100%. [2] N utilization efficiency (NUtE)= grain yield/above-ground dry matter N. [3] NUE$_{crop}$ = grain N/(N fertilizer + N fixation + N transfer); ≥1 indicates N was removed, whereas, values ≤1 show N was added to the field. [4] Means (*n*=20) followed by the same letter are not significantly different (*p*>0.05). [5] nd= no data available because crop was not grown in this specific treatment.

At the end of the growing season, treatment differences were observed for the amount of N removed from the field, where PO 0 N and PMono removed the most N compared to PO ½ N and OMono, which removed the least (**Table 15**). NUEcrop values of one demonstrate optimum fertilizer application; therefore, OMono received the most optimal fertilizer rate between these treatments. Similar to the PO analysis, PMono had the largest pea %NHI compared to PC intercrops. On average, its NHI was 8% higher than the PC intercrops (**Table 15**). Conversely, PC ½ N produced comparable canola %NHI to CMono, but PC 0 N and PC ¼ N were 9% and 8% lower than CMono, respectively.

The yield produced per unit of DMNa demonstrated that PMono was, on average, 8% more efficient than pea in PC intercrops, but canola NUtE was comparable amongst all treatments. Nitrogen fertilizer rate did not impact pea or canola NUtE in the intercrops. At the end of the growing season, PC 0 N and PMono removed the most N from the field and PC ½ N and CMono added N. This was similar to the findings in the PO analysis. Because NUEcrop values of one represent optimal N inputs, PC ½ N received the most optimal N inputs, while CMono added additional N to the field that was not utilized by the crop.

When comparing the NUE of pea in PO and PC intercrops, PC was more efficient than PO (**Table 15**). The PC intercrop had pea NHI 16% higher than PO and pea NUtE 22% higher than PO. Additionally, the PO intercrop removed more N from the field than the PC intercrop at the end of the season. Nitrogen fertilizer rates did not impact pea NHI or NUtE within the intercrops but did influence NUEcrop. The 0 N rate removed the most N from the field and NUEcrop decreased with increasing fertilizer rate, leading ½ N to achieve the most optimal N input, with a value of 1.1.

Table 15. Nitrogen use efficiency indicators of pea-oat (PO) and pea-canola (PC) intercrops. Intercrops received three N fertilizer rates (0, ¼, ½ of recommended). The intercrops, N fertilizer rates, and their interaction were analyzed but only significant interactions are shown. Results are the combined analysis of five sites.

		Pea % NHI[1]	Pea NUtE[2]	NUE_{crop}[3]
Intercrop	PO	58.1 b[4]	13.8 b	1.7 a
(*n*=60)	PC	67.3 a	16.8 a	1.3 b
Fertilizer Rate	0 N	65.9	15.9	1.9 a
(*n*=40)	¼ N	62.3	15.3	1.4 b
	½ N	60.4	14.7	1.1 c
***p*-values**				
Intercrop (I)		**<0.001**	**<0.001**	**<0.001**
Fertilizer Rate (F)		0.061	0.120	**<0.001**
I x F		0.420	0.394	0.384

[1] N harvest index (NHI)= grain N/above-ground dry matter N x 100%. [2] N utilization efficiency (NUtE)= grain yield/above-ground dry matter N. [3] NUE_{crop} = grain N/(N fertilizer + N fixation + N transfer); ≥1 indicates N was removed, whereas, values ≤1 show N was added to the field. Means followed by the same letter are not significantly different (*p*>0.05).

7. Soil residual mineral nitrogen

Post-harvest soil mineral N was 29% higher for the PMono treatment than the PO intercrops (**Table 16**). The low mineral N of PO 0 N and PO ½ N were 13% and 9% lower than OMono, respectively, while PO ¼ N was comparable to OMono. This trend was altered when PC intercrops were grown and compared to their respective monocrops. The PC ½ N was comparable to PMono, but PC 0 N and PC ¼ N had 20% and 22% less soil mineral N than PMono, respectively. All three PC intercrops had soil mineral N similar to CMono after harvest. For both PO and PC analyses, none of the test sites observed differences in ammonium; therefore, treatment differences in soil mineral N were produced because of differences in nitrate.

Table 16. Fall soil mineral N content (kg N ha^{-1}) after growing pea-oat (PO) and pea-canola (PC) intercrops compared to their respective monocrops (PMono, OMono, CMono). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea, which received no N fertilizer. Soil was collected from 0-30 cm depths. Results are the combined analysis of five sites.

Pea-Oat		Pea-Canola	
PO 0 N	22.6 d	PC 0 N	25.5 bc
PO ¼ N	24.8 bc	PC ¼ N	25.0 c
PO ½ N	23.4 cd	PC ½ N	27.8 ab
PMono	30.5 a	PMono	30.5 a
OMono	25.6 b	CMono	25.4 bc

p<0.001	**p=0.007**

Means (n=20) followed by the same letter are not significantly different (p>0.05).

Interactions between intercrops and N fertilizer rates allowed PC ½ N to have the most mineral N present after the growing season (**Table 17**). On average, PC ½ N had 18% more soil mineral N post-harvest than PO. Fertilizer rate impacted soil mineral N differently between both intercrops. Within PC intercrops, mineral N decreased from ½ N > 0 N > ¼ N compared to PO intercrops, where mineral N decreased from ¼ N > ½ N > 0 N.

Table 17. Post-harvest soil mineral N (kg N ha^{-1}) as affected by pea-oat (PO) and pea-canola (PC) intercrops and N fertilizer application rates. Intercrops received three N fertilizer rates (0, ¼, ½ of recommended). Soil was collected from 0-30 cm depths. Results are the combined analysis of five sites.

Soil mineral N		
Intercrop	**PO**	23.6 b
(n=60)	**PC**	26.1 a
Fertilizer Rate	**0 N**	24.1
(n=40)	**¼ N**	24.9
	½ N	25.5
Intercrop x Fertilizer Rate	**PO 0 N**	22.6 d
(n=20)	**PO ¼ N**	24.8 bc
	PO ½ N	23.4 cd
	PC 0 N	25.5 b
	PC ¼ N	25.0 bc
	PC ½ N	27.8 a
***p*-values**		
Intercrop (I)		**<0.001**
Fertilizer Rate (F)		0.103
I x F		**0.011**

Means followed by the same letter are not significantly different (p>0.05).

8. Effects of intercropping on soil water extractable nutrient levels

The WEOC and WEON data in **Table 18** showed a slight variation between the intercrop and monocrop systems, with the monocrop having a marginally higher WEOC (0.31% increase) and WEON (2.82% increase). Within intercrops, the WEOC remained fairly consistent, while the WEON was slightly higher in PC (2.88% increase over PO). Under different fertilization levels, a trend was evident where an increase in N reduced WEON by 6.1% for the ¼N treatment and 8.1% for the ½N treatment in PO intercrops. On the other hand, PC intercrops experienced a WEON increase with higher N, peaking at a 15.0 kg WEON ha^{-1} at the ½N rate, which is a substantial 9.49% increase from the 0N rate.

Table 18. Responses of water extractable organic carbon (WEOC) and nitrogen (WEON) to different cropping systems. The systems examined include various pea-canola and pea-oat intercrops with differing N inputs: PC1/4, a pea-canola intercrop with ¼ N input; PC0N, a pea-canola intercrop with 0 N input; PC1/2N, a pea-canola intercrop with ½ N input; PO1/2N, a pea-oat intercrop with ½ N input; PO1/4N, a pea-oat intercrop with ¼ N input; PO0N, a pea-oat intercrop with 0 N input. Monocrop analyzed include canola monocrop, pea monocrop, and oat monocrop. Samples were collected before planting the subsequent crop, wheat, to evaluate the impact of these intercrops and monocrops on soil fertility.

		WEOC	WEON
Crop System	**Intercrop**	95.6	14.2
	Monocrop	95.9	14.6

Intercrop	**PO**	95.5	13.9
	PC	95.9	14.3
Fertilization	**0N**	95.9	14.8
	1/4N	95.4	13.5
	1/2N	95.8	13.9
Intercrop x Fertilizer Rate	**PO0N**	99.5a	15.9a
	PO¼N	93.3b	12.9b
	PO½N	93.6b	12.9b
	PC0N	92.3b	13.7ab
	PC¼N	97.4a	14.2a
	PC½N	98.0a	15.0a

9. Subsequent wheat performance

9.1 Wheat yield and biomass production

Wheat yield was not affected by the previous year's cropping system (intercrop vs. monocrop) for PO or PC analyses (**Table 19**), except in Redvers 2022, where PMono increased wheat yield by 23% over PO ½ N. At the same time, PC ½ N produced the lowest wheat yield of all PC intercrops, lower than PMono and CMono. Between the intercrops, PC produced 5% more wheat yield than PO (**Table 20**).

Table 19. Wheat productivity (kg ha^{-1}) following pea-oat (PO) and pea-canola (PC) intercrops and their respective monocrops (PMono, OMono, CMono). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea which received no N fertilizer. The following year, all wheat treatments were fully fertilized. Results are the combined analysis of four sites.

	Wheat Yield	Wheat Straw	Wheat DM[1]
		Pea-Oat	
PO 0 N	338	3614	7366
PO ¼ N	3307	3500	7120
PO ½ N	3120	3282	6685
PMono	3481	3620	7420
OMono	3130	3380	6878
	p=0.083	*p*=0.306	*p*=0.246
		Pea-Canola	
PC 0 N	3514	3741	7554
PC ¼ N	3422	3587	7333
PC ½ N	3363	3577	7299
PMono	3481	3620	7420
CMono	3499	3696	7481
	p=0.804	*p*=0.837	*p*=0.949

[1] DM= above-ground dry matter. Means (yield *n*=16, straw *n*=12, DM_a *n*=12) followed by the same letter are not significantly different (*p*>0.05).

Similarly, no wheat straw differences were observed between the intercrops and their monocrops (**Table 19**), but PC produced 5% more wheat straw than PO (**Table 20**). Lastly, neither intercrop affected wheat DM in the subsequent year compared to their respective monocrops. However, similar to wheat yield and straw, differences between PO and PC intercrops were observed, where PC produced 5% more wheat DM than PO. The N fertilizer rate applied in the intercrop phase did not impact wheat yield, straw, or DM production, but trends developed where increasing the N fertilizer rate decreased wheat productivity.

Table 20. Pea-oat (PO) and pea-canola (PC) intercrops were compared for their subsequent wheat productivity (kg ha^{-1}). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended) and in the following year, all wheat treatments were fully fertilized. Results are the combined analysis of four sites.

		Wheat Yield	Wheat Straw	Wheat DM[1]
Intercrop	PO	3268 b	3465 b	7057 b
(*n*=48)	PC	3433 a	3636 a	7398 a
Fertilizer Rate	0 N	3448	3678	7460
(*n*=36)	¼ N	3364	3542	7222
	½ N	3241	3430	6992
***p*-values**				
Intercrop Type (I)		**0.009**	**0.038**	**0.038**
Fertilizer Rate (F)		0.077	0.092	0.091
I x F		0.814	0.835	0.581

[1] DM= above-ground dry matter. Means (straw and DMₐ intercrop *n*=36 and fertilizer rate *n*=24) followed by the same letter are not significantly different (*p*>0.05).

9.2 Wheat nitrogen uptake and nitrogen use efficiency

In the second year of the rotation, wheat grain N was highest following PO 0 N, PO ¼ N, and PMono (**Table 21**). Wheat grain N uptake following the PO intercrops typically decreased with increasing N fertilizer rates, but all three intercrops were comparable to OMono. This differed from the PC intercrops, where no wheat grain N differences were observed between intercrops and monocrops. Nonetheless, the PC intercrop increased wheat grain N by 6% compared to the PO intercrop (**Table 22**). Although no statistical difference was seen for N fertilizer rates, **Table 22** displayed a general trend where wheat grain N decreased as the fertilizer rate increased.

Table 21. Wheat N uptake (kg ha^{-1}) following pea-oat (PO) and pea-canola (PC) intercrops and their respective monocrops (PMono, OMono, CMono). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea which received no N fertilizer. The following year, all wheat treatments were fully fertilized. Results are the combined analysis of three sites.

	Wheat Grain N	Wheat Straw N	Wheat DMN[1]
		Pea-Oat	
PO 0 N	97.2 ab[2]	21.5 a	118.6 ab
PO ¼ N	93.9 abc	20.9 a	114.8 abc
PO ½ N	86.5 c	18.3 b	104.9 c
PMono	101.8 a	22.4 a	124.2 a
OMono	91.4 bc	19.1 ab	110.5 bc
	***p*=0.025**	***p*=0.033**	***p*=0.023**
		Pea-Canola	
PC 0 N	99.2	23.1	122.2
PC ¼ N	98.2	21.3	122.1
PC ½ N	98.9	21.6	121.2
PMono	101.8	22.4	124.2

CMono	100.8	23.0	123.9
	p=0.780	*p*=0.282	*p*=0.751

[1] DMN= above-ground dry matter N. [2] Means (*n*=12) followed by the same letter are not significantly different (*p*>0.05).

Wheat straw N uptake followed a similar pattern to wheat grain N uptake, where all three PO intercrops were comparable to OMono (**Table 21**). At the same time, PO 0 N and PO ¼ N were comparable to PMono, but PO ½ N decreased wheat straw N by 22% compared to PMono. Additionally, the PC intercrop showed no wheat straw N differences compared to its monocrops, but produced 9% more wheat straw N than PO. Wheat straw N decreased with increasing N fertilizer rates (**Table 22**).

The wheat DMNa followed similar patterns to wheat grain N and straw N described above. The PO 0 N and PO ¼ N produced comparable wheat DMNa as PMono and DMNa generally decreased as N fertilizer rates increased, but all three intercrops were similar to OMono (**Table 21**). No differences were observed between PC intercrops and their respective monocrops; however, PC intercrops produced 7% more wheat DMNa than PO intercrops (**Table 22).** Similar to wheat grain N, no statistical differences were observed for N fertilizer rates, but wheat DMNa generally decreased with increasing fertilizer rate. The NUE of wheat was not impacted by the previous year's cropping system (intercrops vs. monocrops), as no differences in wheat %NHI and NUtE were observed. Similarly, no differences were determined between the intercrops or N fertilizer rates for wheat NUE.

Table 22. Pea-oat (PO) and pea-canola (PC) intercrops were compared for their subsequent wheat N uptake (kg ha^{-1}). Intercrops received three N fertilizer rates (0, ¼, ½ of recommended) and in the following year, all wheat treatments were fully fertilized. Results are the combined analysis of three sites.

		Wheat Grain N	Wheat Straw N	Wheat DMN[1]
Intercrop	PO	92.5 b[2]	20.2 b	112.8 b
(*n*=36)	PC	98.8 a	22.0 a	121.8 a
Fertilizer Rate	0 N	98.2	22.3 a	120.4
(*n*=24)	¼ N	96.0	21.1 ab	118.1
	½ N	92.4	20.0 b	112.7
***p*-values**				
Intercrop Type (I)		**0.017**	**0.022**	**0.009**
Fertilizer Rate (F)		0.093	**0.017**	0.058
I x F		0.360	0.777	0.358

[1] DMN= above-ground dry matter N. [2] Means followed by the same letter are not significantly different (*p*>0.05).

9.3 Nitrogen use efficiency in intercrop-wheat rotations

Nonetheless, differences were observed for NUE over the two years of this study. Due to the straw swap methodology, above-ground (%NREra) and below-ground (%NRErb) residue from the intercrop phase could be analyzed individually for their recovery efficiency in the subsequent wheat crop. Wheat recovered a larger percentage of the monocrops' above-ground residue than the PO ½ N and PC ½ N intercrops' above-ground residue (**Figure 7**). However, %NREra was small and did not contribute much to total %NREr. On average, it only had a 4% recovery rate. Therefore, total %NREr followed trends similar to %NRErb, where no differences were seen between treatments. The below-ground residue had a much higher recovery rate than the above-ground residue, averaging 22%. Overall, an average of 28% of crop residue N from the intercrop phase was recovered, leaving 72% of that crop residue N vulnerable to losses.

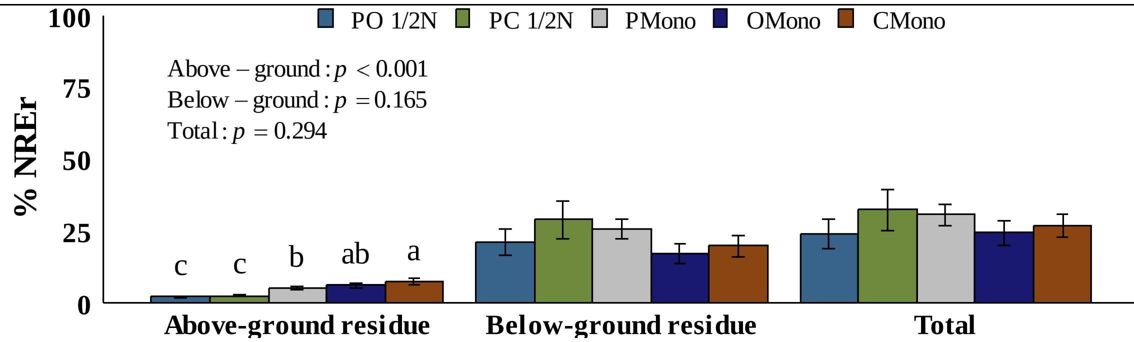

Figure 7. Nitrogen recovery efficiency of crop residue (%NREr) in wheat. Pea-oat (PO) and pea-canola (PC) intercrops were grown, along with their respective monocrops (PMono, OMono, CMono) in the first year of the crop rotation, followed by a subsequent wheat crop. Intercrops were supplied with ½ their recommended rate of N fertilizer and the monocrops received their full recommendation of N, except pea which received no N fertilizer. The following year, wheat was fully fertilized. The percentage of above-ground residue, below-ground residue, and total residue recovered by wheat was determined using the 15N dilution method. Different letters show significant differences between treatments for the recovery of different crop residue sources. Results are the combined analysis of three sites. P≤0.05 were considered significant and bars are means with standard errors (n=12).

Furthermore, %Ndfr demonstrated the percentage of wheat's N requirements that the previous year's crop residue fulfilled. This was only calculated for the above-ground crop residue (%Ndfra) because root analysis was not performed in this study to accurately measure %Ndfr below-ground crop residue (%Ndfrb). Nitrogen derived from residue followed similar trends to %NREra, where the three monocrops had higher %Ndfra than the intercrops. However, in Melfort cycle I, %Ndfra was comparable between the intercrops and OMono, and no differences were observed between treatments in Melfort cycle II. **Figure 8** shows that wheat benefited most from PMono and CMono residue. They contributed 1.1% (PMono) and 1.0% (CMono) of wheat's DMNa, compared to PO ½ N and PC ½ N, which only contributed 0.3% and 0.4% of wheat's DMNa, respectively.

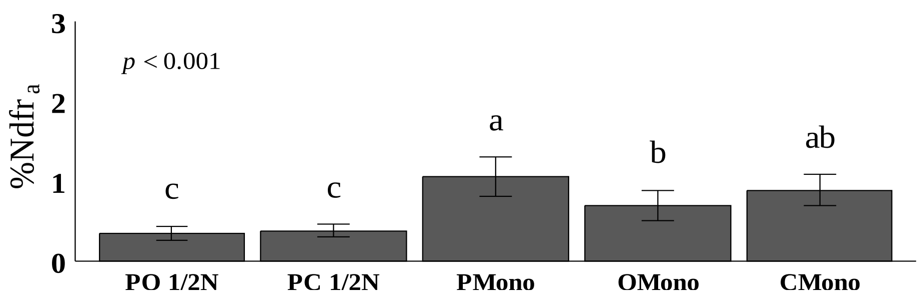

Figure 8. Percentage of wheat N that was derived from above-ground crop residue (%Ndfra). Pea-oat (PO) and pea-canola (PC) intercrops were grown, along with their respective monocrops (PMono, OMono, CMono) in the first year of the crop rotation, followed by a subsequent wheat crop. Intercrops were supplied with ½ their recommended rate of N fertilizer and the monocrops received their full recommendation of N, except pea which received no N fertilizer. The following year, wheat was fully fertilized. The 15N dilution method enabled us to trace the N from above-ground residue in the first year into the following wheat crop. Results are the combined analysis of three sites. P≤0.05 were considered significant and bars are means with standard errors (n=12).

At the end of the two-year cropping rotation, NUEcrop determined if the soil was depleted of N over the two years or if N was added to the field. The PO 0 N and PMono treatments removed the most N from the field (**Table 23**). Values of one show optimal N input; therefore, OMono received its optimal N input over the two-year cropping rotation. The PC intercrop followed similar trends, where PC 0 N and PMono removed the most N from the field, and PC ½ N and CMono received the most optimal N fertilizer rates.

Table 23. Nitrogen use efficiency (NUE_{crop}) over a two-year cropping rotation. Pea-oat (PO) and pea-canola (PC) intercrops and their respective monocrops (PMono, OMono, CMono) were grown in the first year, followed by wheat in the second year. Intercrops received three N fertilizer rates (0, ¼, ½ of recommended); monocrops received their full N recommendation, except pea which received no N fertilizer. The following year, all wheat treatments were fully fertilized. Results are the combined analysis of three sites.

Pea-Oat		***Pea-Canola***	
PO 0 N	1.4 a	PC 0 N	1.3 a
PO ¼ N	1.2 b	PC ¼ N	1.1 b
PO ½ N	1.1 c	PC ½ N	0.9 bc
PMono	1.3 ab	PMono	1.3 a
OMono	1.0 c	CMono	0.9 c
	***p*<0.001**		***p*<0.001**

NUE_{crop} = (intercrop grain N + wheat grain N)/(intercrop fertilizer N + N fixation + N transfer + wheat fertilizer N); ≥1 indicates N was removed, whereas, values ≤1 show N was added to the field after harvest. The different letters in a column are significantly different ($p < 0.05$).

The PO intercrop removed more N from the soil than PC (**Table 24**). The most soil N was removed from the lowest N fertilizer rate, which decreased as more N fertilizer was applied, with the ½ N rate being the optimal N fertilizer rate. Observing the actual inputs/outputs at each site, Swift Current cycle I demonstrated that all treatments increased N, Melfort cycle I had additions and removals, and then Melfort cycle II generally removed N from the field after the study concluded. That being said, all three sites followed similar trends, where more N was available following treatments that received more N fertilizer.

Table 24. Comparing two-year N use efficiency of pea-oat (PO) and pea-canola (PC) intercrops, followed by wheat in the second year. Intercrops received three N fertilizer rates (0, ¼, ½ of recommended) and wheat was fully fertilized. Results are the combined analysis of three sites.

		$\mathbf{NUE_{crop}}$[1]
Intercrop Type	PO	1.2 a[2]
(*n*=36)	PC	1.1 b
Fertilizer Rate	0 N	1.3 a
(*n*=24)	¼ N	1.1 b
	½ N	1.0 c
***p*-values**		
Intercrop Type (I)		**0.011**
Fertilizer Rate (F)		**<0.001**
I x F		0.915

[1] NUE_{crop} = (intercrop grain N + wheat grain N)/(intercrop fertilizer N + N fixation + N transfer + wheat fertilizer N); ≥1 indicates N was removed, whereas, values ≤1 show N was added to the field after harvest. [2] Means followed by the same letter are not significantly different ($p>0.05$).

10. Effects of intercropping on diseases

10.1 Diseases in the first year of phase I (2021)

At Swift Current, no disease was observed in any crop or treatment in the first year of phase I (2021). This was unsurprising, given the hot dry conditions and the use of a preventative fungicide (Priaxor) application. Melfort had no disease symptoms in pea, oat or canola in 2021. It is surprising that no root rot symptoms were present. However, dry conditions and site-to-site variability likely explain this.

Redvers had disease in pea, but not oat or canola. Although, both mycosphaerella blight and root rot severity were quite low. The heat and drought in 2021 likely contributed to this. The late planting date probably added to this impact because the plants were maturing later in the season and thus exposed to even higher temperatures. There were no differences between treatments for either disease (**Figure 9**). Later rating of root rot also potentially reduced the likelihood for treatments being different because, as roots get older, senescence can make root rot symptoms harder to rate. In addition, saprophytic organisms can colonize the roots later in the season. The results of the first year in phase I showed that intercropping pea with oat or canola did not impact disease under low disease pressure.

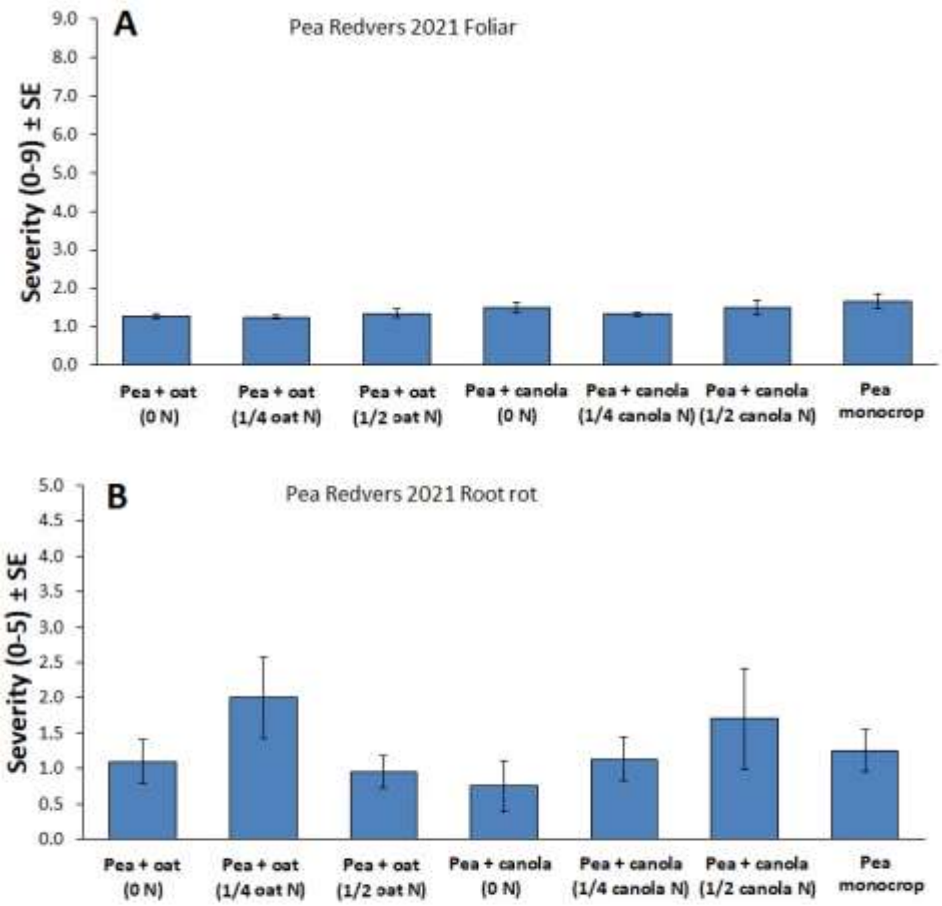

Figure 9. Mycosphaerella blight (A) and root rot (B) in pea at Redvers in the first year of phase I (2021). There were no differences between treatments (P-value ≤ 0.05).

10.2 Diseases in the first year of phase II (2022)

At Redvers, intercropping with pea significantly reduced the severity of leaf spot or blotch in oat in the first year of phase II (2022) (**Figure 10A**). These results are consistent with the impact of intercropping on other foliar crop diseases, such as Mycosphaerella blight of pea (Fernández-Aparicio et al., 2010, Schoeny et al., 2010) chocolate spot of faba beans (Guo et al., 2020, Fernández-Aparicio et al., 2011) and Ascochyta blight of chickpea (Hubbard et al, unpublished data). Potential mechanisms include dilution of host plants, pea providing a physical barrier to the spread of inoculum, changes in the humidity of temperature within the crop canopy, and/or triggering of oat defense responses. Redvers had severe root rot and very mild mycosphaerella blight in pea. There were no differences between treatments (**Figure 10B and C**). The root rot data demonstrates that, at least at these site-years, neither intercropping with oat nor with canola is a viable method of managing severe root rot. These results are consistent with those obtained in other recent or concurrent trials on pea-brassica or pea-oat intercropping in the Canadian prairies, which focused on assessing the value of intercropping as a root rot management tool (Hubbard et al., unpublished data). The root rot severity was much higher in 2022 than in 2021. For mycosphaerella blight, the disease pressure may have been too light to fully assess the impact(s) of intercropping with oat or canola. No data was collected on sclerotinia or blackleg of canola at Redvers in 2022. At Swift Current, all crops and treatments received a rating of zero in the first year of phase II. Melfort had no disease symptoms in pea, oat or canola in the first year of phase II.

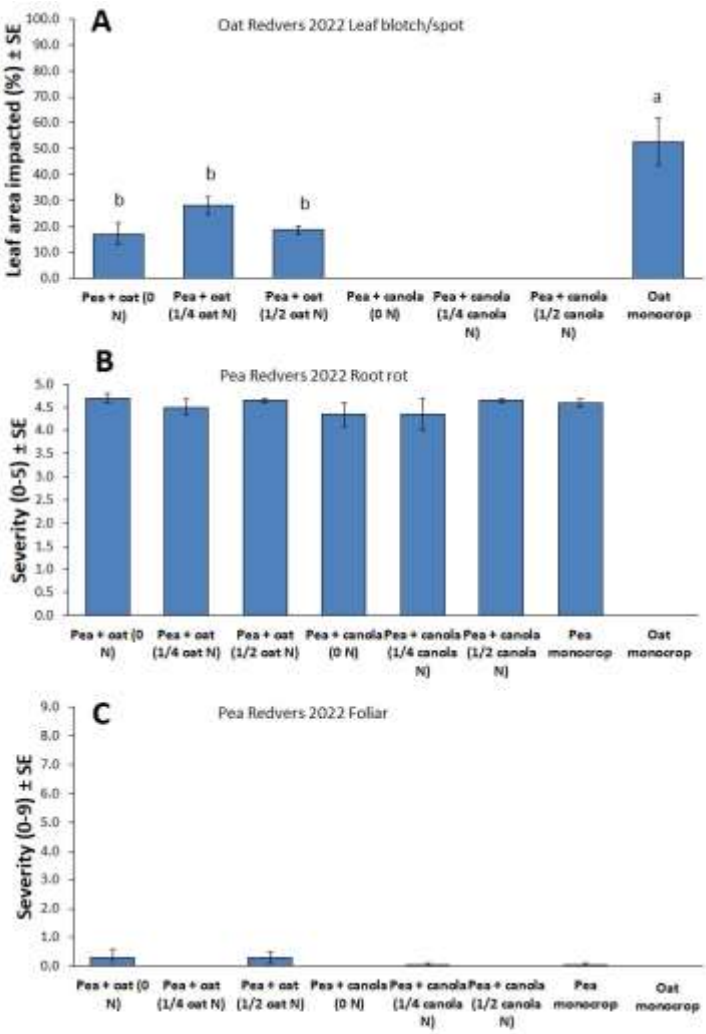

Figure 10. Leaf disease in oat (A), as well as root rot (B) and mycosphaerella blight (C) in pea at Redvers in 2022. For oat disease, bars with the same letter are not significantly different (P-value ≤ 0.05). There were no differences between treatments for pea disease.

11. Crop lodging and maturity days

In five out of six site-years, the average lodging rates across all treatments were at 1, indicating no lodging occurred at crop harvest with an exception of Redvers in the first year (2022) of phase II (**Table 25**). At Redvers in 2022, the lodging rate for canola monocrops and pea-canola intercrops reached light to medium levels. The variation in the days to maturity for each crop at each site was minimal, but the variation was greater between the two growing seasons. Compared to the first year (2021) of phase I, most crops had a loner average days to maturity in the first year (2022) of phase II, with Melfort experiencing the most significant increase. Specifically, the average days to maturity for pea, canola and oat in 2022 were 29, 19 and 24 days longer at Melfort compared to 2021; they were 0, -2 and 11 days longer at Redvers; and 3, 8, 6 days longer at Swift Current.

Table 25. Lodging and day to maturity across all treatments at Melfort, Redvers and Swift Current in the first year of phase I (2021) and phase II (2022).

Location	Treatments	Phase I (2021)				Phase II (2022			
		Lodging (1-10)*	Days to maturity (day)			Lodging (1-10)*	Days to maturity (day)		
			Pea	Canola	Oat		Pea	Canola	Oat
Melfort	PO0N	1	72		78	1	101		101
	PO1/4N	1	72		78	1	101		101
	PO1/2N	1	72		77	1	101		101
	PC0N	1	72	81		1	101	101	
	PC1/4N	1	72	82		1	101	101	
	PC1/2N	1	74	83		1	101	101	
	Pmono	1	72			1	101		
	Omono	1			76	1			101
	Cmono	1		83		1		101	
Redvers	PO0N	1	74		76	1	73		86
	PO1/4N	1	75		76	1	74		86
	PO1/2N	1	74		75	1	76		87
	PC0N	1	75	95		3	73	93	
	PC1/4N	1	74	95		4	77	93	
	PC1/2N	1	74	95		5	77	93	
	Pmono	2	76			2	73		
	Omono	1			73	2			85
	Cmono	1		96		4		95	
Swift Current	PO0N	2	86		77	1	83		85
	PO1/4N	1	84		77	1	83		83
	PO1/2N	1	85		77	1	84		84
	PC0N	1	79	87		1	85	95	
	PC1/4N	1	79	87		1	85	94	
	PC1/2N	2	79	87		1	85	94	
	Pmono	1	79			1	85		
	Omono	1			78	1			83
	Cmono	1		86		1		96	

* Plant lodging was rated on scale of 1 (upright) to 10 (flat).

† PO0N = pea and oat intercrop without N fertilizer, PO1/4N = pea and oat intercrop with 1/4 of recommended N rate for oat monocrop, PO1/2N = pea and oat intercrop with 1/2 of recommended N rate for oat monocrop, PC0N = pea and canola intercrop without N fertilizer, PC1/4N = pea and canola intercrop with 1/4 of recommended N rate for oat monocrop, PC1/2N = pea and canola intercrop with 1/2 of recommended N rate for oat monocrop, Pmono = pea monocrop, Omono = oat monocrop, and Cmono = canola monocrop.

12. Intercrop effects on economic returns

12.1 Swift Current

Net revenues for pea, canola and oat monocrops and for the intercrops were negative, although both pea and canola showed statistically similar and higher net revenue than oat monocrop in 2021 (**Table 26**). The negative net return for the three monocrops results from lower gross revenue could be due to drought-caused yield reduction in this site. The net revenue for three monocrops were positive, but they were statistically similar in 2022. Canola ($64 ha^{-1}) and oat ($-77 ha^{-1}) had the highest and lowest net revenue averaged across years, respectively. All the pea-canola and pea-oat intercrops showed statistically similar in both 2021 and 2022. However, net return for pea-oat intercrop without N ($-201 ha^{-1}) was higher than pea-canola with 1/2 N rate ($-334 ha^{-1}) averaged across years. This suggests that pea-oat intercrop without N application can provide better economic return and stability than pea-canola with 1/2 N in the site with lower seasonal precipitation. All the pea-canola intercrops showed no economic advantage over pea and canola monocrops as the net revenues for pea-canola intercrops at any N level were significantly lower than that for pea and canola monocrops in 2021. In 2022, only pea-canola without N showed statistically similar net return with both pea and canola monocrops. None of the pea-oat intercrops showed similar economic benefit over pea and oat monocrops in 2021. Similarly, none of the pea-oat intercrops displayed similar net return with both pea and oat monocrops in 2022. But, intercrops pea-oat without N ($94 ha^{-1}) and pea-oat with 1/2 N ($75 ha^{-1}) had statistically similar net returns with oat monocrop ($279 ha^{-1}) in 2022, suggesting their partial economic suitability as intercrop. This can be further documented by across years analysis where, pea-oat intercrop without N ($-201 ha^{-1}) had statistically similar net revenue with oat monocrop ($-77 ha^{-1}) averaged across years. Beily-Elkin et al. (2022) found variable net returns for pea-oat intercrops such as an increased net return under weedy situation, but a decreased net return under low weed pressure in Carman, MB. The results obtained here indicate that overall pea-oat intercrop without N application can partly maintain economical benefit similar to monocrop under variable precipitation conditions.

Table 26. Least square means of net revenue ($ ha^{-1}) of pea, canola and oat monocrops and their intercrops (pea-canola and pea-oat) with 0, 1/2 and 1/4 of recommended N rates of canola and oat at Swift Current, SK during 2021-2022. Least square means sharing the same letter are not statistically significant at $p < 0.05$.

Treatments	2021	2022	Across years
Pea	-239[a]	309[a]	35[ab]
Canola	-132[a]	260[abc]	64[a]
Oat	-432[b]	279[ab]	-77[bc]
Pea-canola 0 N	-501[bc]	69[cd]	-216[de]
Pea-canola 1/4 N	-552[bc]	35[d]	-259[de]
Pea-canola 1/2 N	-609[c]	-59[d]	-334[e]
Pea-oat 0 N	-495[bc]	94[bcd]	-201[cd]
Pea-oat 1/3 N	-549[bc]	57[cd]	-246[de]
Pea-oat 1/2 N	-582[c]	75[bcd]	-254[de]
***p*-value**	<0.001	<0.001	<0.001

12.2 Redvers

Pea ($425 ha^{-1}) had higher net revenue than oat ($-10 ha^{-1}) in 2021. Both canola ($724 ha^{-1}) and oat ($538 ha^{-1}) resulted in statistically similar and higher net revenue than pea ($-555 ha^{-1}) in 2022. Net return for canola ($535 ha^{-1}) was higher than that for pea ($-65 ha^{-1}) across years (**Table 27**). Net returns for pea-canola and pea-oat intercrops were basically similar in 2021, 2021 and across years. Pea-canola intercrops maintained similar net returns with their pea ($425 ha^{-1}) and canola ($346 ha^{-1}) monocrops in 2021. Similarly, all pea-oat intercrops showed similar economic benefit with their pea and oat monocrops. In 2022, pea-canola with both 1/4 and 1/2 N displayed statistically similar net returns with pea and canola monocrops suggesting greater intercropping economic benefit than pea-canola without N. On the other hand, all pea-oat intercrops had similar net returns with both pea and oat monocrops in 2022. However, averaged across years, only pea-canola with 1/4 N showed statistical similar net revenue with both pea and canola monocrops, while all pea-oat intercrops showed similar net returns with their pea and oat monocrops.

Table 27: Least square means of net revenue ($ ha^{-1}) of pea, canola and oat monocrops and their intercrops (pea-canola and pea-oat) with 0, 1/2 and 1/4 of recommended N rates of canola and oat at Redvers, SK during 2021-2022. Least square means sharing the same letter are not statistically significant at $p < 0.05$.

Treatments	2021	2022	Across years
Pea	425^{a}	-555^{c}	-65^{b}
Canola	346^{ab}	724^{a}	535^{a}
Oat	-10^{b}	538^{ab}	264^{ab}
Pea-canola 0 N	350^{ab}	-211^{bc}	69^{b}
Pea-canola 1/4 N	247^{ab}	90^{abc}	168^{ab}
Pea-canola 1/2 N	250^{ab}	-31^{abc}	110^{b}
Pea-oat 0 N	101^{ab}	77^{abc}	89^{b}
Pea-oat 1/4 N	137^{ab}	146^{abc}	141^{ab}
Pea-oat 1/2 N	115^{ab}	47^{abc}	81^{b}
***p*-value**	0.013	<0.001	0.004

12.3 Melfort

Both pea ($124 ha^{-1}) and oat ($57 ha^{-1}) had significantly higher net revenue than canola ($-358 ha^{-1}) in 2021. Canola ($1286 ha^{-1}) showed higher net revenue than both pea ($530 ha^{-1}) and oat ($544 ha^{-1}), which showed statistically similar in 2022. Three monocrops demonstrated statistically similar economic benefit across years (**Table 28**). All the pea-canola and pea-oat intercrops showed negative net revenue and statistically similar except significantly higher economic return for pea-oat intercrop with 1/4 N ($-87 ha^{-1}) than that for pea-canola with 1/2 nitrogen ($-342 ha^{-1}) in 2021. In contrast, net revenues for all the pea-canola and pea-oat intercrops were positive and statistically similar except significantly higher net revenue for pea-canola with ¼ N ($1098 ha^{-1}) than that for pea-oat with ½ N ($498 ha^{-1}) in 2022. Higher economic return for pea-canola with 1/4 N than pea-oat with 1/2 N is mainly due to higher canola price than oat. However, pea-canola and pea-oat intercrops showed statistically similar economic benefit across years. The net returns for pea-canola intercrops were negative and statistically similar with canola ($-358 ha^{-1}) monocrop, but were significantly lower than pea ($124 ha^{-1}) monocrop in 2021. Intercrop pea-oat without N ($-76 ha^{-1}) had similar economic return with both pea ($124 ha^{-1}) and oat ($57 ha^{-1}) monocrops in 2021. Pea-oat with 1/4 N ($-87 ha^{-1}) had also similar net return with oat monocrop ($57 ha^{-1}), but had lower net revenue than pea ($124 ha^{-1}) in 2021. Pea-canola intercrops ($928-$1098 ha^{-1}) showed statistically similar net returns with their pea ($530 ha^{-1}) and canola ($1286 ha^{-1}) monocrop in 2022. Similarly, pea-oat intercrops ($498-$533 ha^{-1}) displayed statistically similar economic benefit with pea ($530 ha^{-1}) and oat ($544 ha^{-1}) monocrops in 2022. Net returns for pea-canola ($293-$431 ha^{-1}) and pea-oat ($144-$229 ha^{-1}) intercrops were also statistically similar with their monocrops (Pea $427 ha^{-1}, Canola $464 ha^{-1} and Oat $301 ha^{-1}) when they were analyzed across years. The results suggested that both pea-canola and pea-oat intercrops maintained similar economic benefit compared to their sole crops in this location.

Table 28. Least square means of net revenue ($ ha^{-1}) of pea, canola and oat monocrops and their intercrops (pea-canola and pea-oat) with 0, 1/2 and 1/4 of recommended N rates of canola and oat at Melfort, SK during 2021-2022. Least square means sharing the same letter are not statistically significant at $p < 0.05$.

Treatments	2021	2022	Across years
Pea	124[a]	530[bc]	427[ab]
Canola	-358[d]	1286[a]	464[a]
Oat	57[ab]	544[bc]	301[ab]
Pea-canola 0 N	-184[cd]	1039[abc]	293[ab]
Pea-canola 1/4 N	-235[cd]	1098[ab]	327[ab]
Pea-canola 1/2 N	-342[d]	928[abc]	431[ab]
Pea-oat 0N	-76[abc]	533[bc]	229[ab]
Pea-oat 1/4 N	-87[bc]	529[bc]	221[ab]
Pea-oat 1/2 N	-211[cd]	498[c]	144[b]
***p*-value**	<0.001	<0.001	0.028

12.4 Across locations and years

There were also no statistical differences among the monocrops (Pea \$103 ha^{-1}, Canola \$-48 ha^{-1}, and Oat \$-129 ha^{-1}) across locations in 2021 (**Table 29**). Pea-canola and pea-oat intercrops showed negative net revenue and they were statistically similar across locations in 2021. The negative net revenue for both pea-canola and pea-oat intercrops can be explained by low grain yields which generated low gross revenue due to inadequate precipitation across locations in 2021. Both pea-canola and pea-oat without N showed statically similar net returns with their monocrops across locations in 2021. This implies that either pea-canola or pea-oat intercrop with higher N levels has no economical advantage compared to the monocrops regardless of soil conditions in the case of inadequate precipitation. Canola (\$756 ha^{-1}) had the highest net revenue followed by oat (\$454 ha^{-1}) and pea (\$95 ha^{-1}) showed the lowest as a sole crop across locations in 2022. All the pea-canola (\$279-\$408 ha^{-1}) and pea-oat (\$207-\$244 ha^{-1}) intercrops showed statistically similar net revenue across locations in 2022. However, none of the pea-canola intercrops was similar economic benefit with both pea and canola monocrops across locations in 2022. For example, pea-canola with 1/4 N showed significantly higher economic benefit than pea, but had lower net return than canola. Moreover, pea-canola with 1/2 N displayed statistically similar net return with pea monocrop, but had lower economic advantage than canola monocrop. This indicates that pea-canola with 1/4 N had a great potential to improve intercropping economic benefit across locations under adequate precipitation. On the other hand, all pea-oat intercrops showed statistically similar net returns with pea and oat monocrops across locations in 2022. Comparing both years, this suggests that pea-oat intercrop without N showed greater stability in net revenue over different precipitations regardless of soil conditions. This can be further explained by the fact that all the pea-oat intercrops generated statistically similar net revenue with their pea and oat monocrops across locations and years.

Table 29. Least square means of net revenue (\$ ha^{-1}) of pea, canola and oat monocrops and their intercrops (pea-canola and pea-oat) with 0, 1/2 and 1/4 of recommended N rates of canola and oat (a) across locations and years, (b) across locations in 2021, and (c) across locations in 2022. Least square means sharing the same letter are not statistically significant at $p < 0.05$.

Treatments	Across sites in 2021	Across sites in 2022	Across sites and years
Pea	103[a]	95[c]	99[b]
Canola	-48[ab]	756[a]	354[a]
Oat	-129[ab]	454[b]	162[b]
Pea-canola 0 N	-112[ab]	299[bc]	94[b]
Pea-canola 1/4 N	-180[b]	408[b]	114[b]
Pea-canola 1/2 N	-234[b]	279[bc]	23[b]
Pea-oat 0N	-157[ab]	235[bc]	39[b]
Pea-oat 1/4 N	-166[b]	244[bc]	39[b]
Pea-oat 1/2 N	-226[b]	207[bc]	-10[b]
***p*-value**	<0.001	<0.001	<0.001

Overall, in Swift Current, all the pea-canola intercrops showed no economic advantage over pea and canola monocrops in 2021, but only pea-canola without N showed statistically similar net return with both pea and canola monocrops in 2022. Overall pea-oat intercrop without N application can partly maintain economical benefit similar to monocrop. In Redvers, averaged across years, only pea-canola with 1/4 N showed statistical similar net revenue with both pea and canola monocrops, while all pea-oat intercrops showed similar net returns with their pea and oat monocrops. In Melfort, pea-canola and pea-oat intercrops showed statistically similar economic benefit across years and both pea-canola and pea-oat intercrops maintained similar economic benefit compared to their sole crops in this location. Both pea-canola and pea-oat without N showed statically similar net returns with their monocrops across locations in 2021. This implies that either pea-canola or pea-oat intercrop with higher N levels has no economical advantage compared to the monocrops.

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Conclusions and Recommendations *(maximum 500 words)*

Highlight significant conclusions based on the findings of this project, with emphasis on the project objectives specified above. Provide recommendations for the application and adoption of the project findings.

Based on the findings in this 3-year study, we draw the following conclusions:

- Based on the land equivalent ratio (LER), intercropping systems resulted in a 1-3% increase in grain yield per unit of land area compared to monoculture in 2021 and a 23-38% increase in 2022 at Melfort and Redvers. However, at Swift Current, intercropping led to a 9-17% reduction in yield relative to monoculture.
- Oat in pea-oat intercrops had a higher plump seed percentage but lower beta-glucan and protein contents than oat monocrop at all sites. Pea-canola intercrop had no effect on canola quality.
- Across all sites, the pea-based intercrop stubbles did not result in an increase in wheat yield compared to the monocrop (either pea, oat, or canola) stubbles. Pea-canola intercrop stubbles increase the following wheat yield by 5% compared with pea-oat intercrop stubbles.

- Nitrogen derived from the atmosphere (%Ndfa) of pea followed the order of pea-oat > pea-canola > pea monocrop. Biological N fixation followed the order of pea monocrop ≥ pea-canola > pea-oat considering yield and biomass production. We believe that N benefits in intercrop are related to the competitiveness of the companion crops. High N fertilizer rates reduced the %Ndfa and total N fixation as high N fertilizer input promotes the companion crop growth. Across all sites, no or limited N transfers from pea to the companion crops (e.g., oat and canola) were observed at most site-years due to the relatively drought conditions.
- Intercrops did not result in economic advantage, with canola monocrop generating the highest net return.
- Intercrops had limited benefits on soil health as indicated by similar level of soil water extractable carbon and nitrogen.
- Pea-based intercropping had minimal effects on pea diseases, and pea-oat intercrop reduced the severity of leaf spot or blotch in oat in 2022.

We recommend

- No nitrogen fertilizer application for pea-oat or pea-canola intercrops to achieve greater mutual benefits within intercrops.
- Adjust seeding rate ratios in intercrops based on their competitiveness to achieve idea component crop ratios and maximize pea benefits

Follow-up Research

Please identify if there is a need to conduct further research. Detail any further research, development and/or communication needs arising from this project.

N/A

Patents/ IP generated/ Commercialized Products

List any products developed from this research.

N/A

Sustainable Canadian Agricultural Partnership (Sustainable CAP) Performance Indicators

a) List of performance indicators for the entire lifespan of the project

Sustainable CAP Indicator	Total Number
Scientific publications from this project (List the publications under section b)	
• Published	
• Accepted for publication	
Highly Qualified Personnel (HQP) trained during this project	

• Master's students	1
• PhD students	
• Post docs	
Knowledge transfer products developed based on this project (presentations, brochures, factsheets, flyers, guides, extension articles, podcasts, videos)[1]	

[1] Please only include the number of unique knowledge transfer products.

b) List of scientific journal articles published/accepted for publication from this project. Please ensure that each line includes the following: **Title, Author(s), Journal, Date Published or Accepted for Publication and Link to Article (if available).** *Add additional lines as needed*.

1. Kennedy Marie Choo-Foo. 2024. Nitrogen acquisition of pea-oat and pea-canola intercrops and their impact on subsequent wheat crops. M.Sc. thesis. University of Saskatchewan. Defended May 13th, 2024

Technology Transfer Activities

List any technology transfer activities. Include presentations to conferences, producer groups or articles published in magazines except scientific journals.

- Liu K., 2022. Spoke about the intercrop project at Melfort field day. July 20, 2022.
- Choo-Foo K. 2022. Spoke about the intercrop project at Swift Current Field Day "Test Innovation". July 12, 2022.
- Choo-Foo K., 2022. Spoke about the intercrop project at the South East Research Farm field day. July 28, 2022.
- Choo-Foo K., Liu K., Knight D. 2022. "Do pea-oat and pea-canola intercrops affect biological nitrogen fixation and nitrogen use efficiency?". AgBio Research Fair, University of Saskatchewan. September 7, 2022 (Poster Presentation).
- Choo-Foo K., Liu K., Knight D. 2023. "Reducing nitrogen fertilizer applications using pea-oat and pea-canola intercrops". Soils and Crops workshop, Prairieland Park, Saskatoon, March 7-8, 2023 (Oral presentation).
- Choo-Foo K., Liu K., Knight D. 2023. "Can pea-oat and pea-canola intercrops reduce fertilizer applications without comprising yield?". Canadian Society of Soil Science annual meeting. Truro, NS. June 26-29, 2023 (Oral presentation).
- Choo-Foo K., Liu K., Knight D. 2023. "How does the nitrogen use efficiency of intercrops impact subsequent wheat yield?". Agriculture Research Day, University of Saskatchewan, Saskatoon. September 20, 2023 (poster presentation).
- Choo-Foo K., Liu K., Knight D. 2024. "Reduce nitrogen fertiliser inputs through pea-oat and pea-canola intercrop". Soils and Crops workshop, Prairieland Park, Saskatoon, March 6-7, 2024 (Oral presentation).

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List any industry contributions or support received.

Saskatchewan Oat Development Commission for providing financial support

General Mills for providing in-kind oat quality analysis

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Appendices

Identify any changes expected to industry contributions, in-kind support, collaborations or other resources.