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Economic analysis of legume-based intercropping across Canadian Prairies

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Abstract

Legume-based intercropping offers a promising strategy because it may improve resource allocation and income stability for growers. Two multi-year intercrop studies were conducted in Swift Current, Melfort (Saskatchewan), Lethbridge (Alberta), and Carman (Manitoba) to assess the financial results of different intercrops, including pea (*Pisum sativum* L.)–canola (*Brassica napus* L.), pea–oat (*Avena sativa* L.), faba bean (*Vicia faba* L.)–malt barley (*Hordeum distichum* L.), malt barley–pea, and corn (*Zea mays* L.)–soybean (*Glycine max* L.) under different nitrogen (N) fertilizer rates. Net return (NR), calculated as total revenue minus total costs, was used to compare intercrops with monocrops. Monetary returns varied by location. While pea–canola and pea–oat did poorly in semi-arid Swift Current, intercropping generally matched or outperformed monocrops and maintained income stability. Applying N fertilizer to legume-based intercrops did not enhance NRs, but enabled an 80% reduction in N application compared to monocrops. This resulted in a cost difference of \$116 ha^{-1}, with monocrops requiring \$132 ha^{-1} and intercrops only \$16 ha^{-1}. Overall, intercropping improved resource use efficiency and income stability, offering farmers a viable approach to sustainable crop production under diverse growing conditions in western Canada.

Key words: cost, diversified cropping systems, intercropping, monocropping, nitrogen application, net return

Introduction

Current farming systems depend on synthetic agrochemicals such as fertilizers and pesticides to boost crop yield. The cost of synthetic agrochemicals is increasing and is projected to increase further, thus increasing financial risks and jeopardizing farm profit (Dowling et al. 2023). To cope with high food demands due to rising population growth, negative environmental externalities, and financial risks, crop diversification is a known option to enhance both ecological and financial benefits (Rosa-Schleich et al. 2019).

Crop diversification can take many forms, including crop rotation, cover crops, and intercropping, as an alternative to intensive monocropping (Wezel et al. 2014). Intercropping can be a popular choice, where different crop species are grown simultaneously on the same piece of land (Rosa-Schleich et al. 2019). Intercropping has demonstrated benefits in crop yield and stability (Ghaley et al. 2005; Dordas et al. 2012; Malhi 2012; Chapagain and Riseman 2014; Bedoussac et al. 2015; Rosa-Schleich et al. 2019; Huss et al. 2022), weed suppression (Rosa-Schleich et al. 2019; Bailey-Elkin et al. 2022; Huss et al. 2022), and pest control (Lithourgidis et al. 2011; Rosa-Schleich et al. 2019; Huss et al. 2022). It also is considered more environmentally friendly as it provides important ecological services and improves resource use efficiency (Fletcher et al. 2020). For example, Huss et al. (2022) noted in their meta-analysis that intercropping may mitigate the effects of climate change by reducing greenhouse gas emissions through increased space efficiency (i.e., reduced energy use), lowering reliance on synthetic fertilizers, minimizing soil erosion, and improving nutrient and water use efficiency. Intercropping practices also increase soil organic carbon and soil water holding capacity, enhancing biodiversity while maintaining crop yield (Morugán-Coronado et al. 2020). Among diverse intercropping combinations, legume–cereal and legume–oilseed systems have gained significant attention. They have potential to enhance nitrogen (N) use efficiency, improve soil health through biological N fixation, and reduce N fertilizer requirements in subsequent cereal and oilseed crops due to the N benefits from legume crop residue (St. Luce et al. 2015; Liu et al. 2019). For instance, faba bean (*Vicia faba* L.)–barley (*Hordeum distichum* L.) and barley–pea (*Pisum sativum* L.) intercropping systems integrate the

N-fixing ability of legumes with the high productivity of cereals, potentially reducing the reliance on synthetic fertilizers while maintaining or increasing overall yields (Trydeman Knudsen et al. 2004). Similarly, corn (*Zea mays* L.)–soybean (*Glycine max* L.) intercropping leverages the N supply from soybean to improve the growth of corn, particularly in regions with high nutritional demand (Layek et al. 2014). Legume crop residues in intercrops accumulate more N compared to non-legume crop residues, affecting nutrient cycling and soil health (Chapagain and Riseman 2014; Cong et al. 2015).

In addition to the above mentioned benefits, intercropping systems offer yield stability, a critical metric for evaluating the resilience of cropping strategies under fluctuating climatic and biotic conditions. Yield stability may lead to income stability at the farm level. Studies suggest that grain legume–barley intercropping generally exhibits less variability than monocropped grain legumes (Hauggaard-Nielsen et al. 2008).

Despite the ecological benefits of intercropping, there are barriers to its adoption. One of the well-documented hurdles is the increased complexity of compatibility and managing multiple crop species with highly specific technologies used in highly mechanized farming systems (Bedoussac et al. 2015; Rosa-Schleich et al. 2019; Huss et al. 2022). Both Rosa-Schleich et al. (2019) and Huss et al. (2022) noted in their reviews that these challenges with farm equipment can lead to increased labour requirements, thus affecting the overall profitability of intercropping. For example, the cost of seed separation after harvesting intercrops is unavoidable, while intercropping two species with similar grain sizes poses additional technological challenges. Further, Liu et al. (2025) showed that while intercropping pea–oat (*Avena sativa* L.) and pea–canola (*Brassica napus* L.) has various advantages, these advantages vary depending on the environment. The study demonstrated higher land productivity by intercrops in sub-humid regions as compared to semi-arid environments. There is also the challenge of understanding and optimizing inputs for an intercropping system due to the different nutritional requirements of the two crops.

Legume–oilseed intercrops, such as pea–canola, may preserve the benefits of intercropping while overcoming some adoption challenges. These combinations offer greater in-season herbicide options since both species are broadleaf plants and facilitate easier seed separation due to their distinct seed sizes, unlike traditional legume–cereal intercrops (i.e., pea and oat) (Fletcher et al. 2020; Dowling et al. 2023). These crops also have complementary root structures and growth patterns that help optimize soil nutrient extraction and improve resilience against pests and diseases. Further, pea–canola intercrops can improve protein-based yield and net return (NR) compared to sole crops under low-input scenarios (e.g., low N application) (VanKoughnet 2016; Dowling et al. 2023; Liu et al. 2025). This is particularly relevant as growers often adopt intercropping to reduce input costs and increase farm profitability. Bailey-Elkin et al. (2022) reported that pea–oat intercropping significantly increased NR compared to sole crops under high weed pressure but not under low weed pressure. Financial implications of legume–oilseed and legume–cereal intercrops vary depending on growing conditions, and are usually comparable to those of sole crops (Fernandez et al. 2015; Bailey-Elkin et al. 2022). While the ecological benefits of these intercropping systems may not immediately offset monetary returns, they have the potential to enhance long-term profitability and reduce financial and agronomic risks (Martin-Guay et al. 2018; Rosa-Schleich et al. 2019).

Despite the well-documented agronomic benefits of intercropping, such as efficient resource use, alleviated pest pressure, reduced crop lodging, and increased yield and post-harvest residues, its financial outcomes remain poorly understood (Struckman 2021; Dowling et al. 2023). Given the high cost of N fertilizer and the rising costs of other essential inputs, identifying a financially viable intercrop is crucial for its profitability, adoption, and long-term environmental impact. This study aimed to (1) assess the financial results of pea–canola and pea–oat intercrops under varying levels of N fertilizer in terms of NR under different soil conditions in Saskatchewan, and (2) compare the monetary returns of pea–canola and faba bean–malt barley, malt barley–field pea, and corn–soybean intercropping systems with their respective monocrops across three additional locations in western Canada. Nitrogen fertilizer rates and application costs for intercropping and monocropping were also evaluated. The findings serve to help growers discover and delineate the most commercially viable cropping systems for their own farm business given common popular alternatives.

Materials and methods

Field experiments

Two separate experiments were conducted over a 5-year period (2018–2022) at various locations in western Canada. In Study 1 (2021–2022), the monetary benefits of pea–canola and pea–oat intercrops with varying levels of N fertilizer in terms of NRs were examined under different soil conditions in Saskatchewan. In Study 2 (2018–2022), cereal and oilseed intercropping with different legume crop cultivars were compared with monocropping systems.

Similar agronomic practices were employed in both studies. In all cases, N fertilizer was applied as indicated by treatment in the detailed description of each study below. A uniform rate of other nutrients was applied across the entire experiment as required to ensure sufficiency based on soil testing of each experimental location.

Study 1. Canola and oat intercropping with peas using varying levels of N fertilizer

The experimental design, agronomic management on crops, data collection of crop performance and yields, and methods and materials have been detailed in a previous publication (Liu et al. 2025); thus, only a summary of the experiment will be provided here.

A multi-location field experiment was undertaken at two different locations (Swift Current and Melfort) to investigate the financial efficiency of different intercropping systems in Saskatchewan, Canada, in 2021 and 2022. An economic analysis compared pea–canola and pea–oat intercrops with

Table 1. Average fertilizer application rate (kg ha^{-1}) and seeding rate (kg ha^{-1}) for different crops used in the intercrops experiment at three sites across Canadian Prairies, 2018–2022.

	N	P_2O_5	K_2O	S	Seeding rate
Swift Current					
Barley–pea Int.	13	17	0	10	74/223
Faba bean–barley mix	13	17	0	10	127/74
Malt barley	64	17	0	10	148
Faba bean	13	17	0	10	170
Pea	13	17	0	10	254
Lethbridge					
Barley–pea Int.	15	44	0	17	93/251
Faba bean–barley mix	15	44	0	17	115/93
Malt barley	78	44	0	18	148
Faba bean	15	44	0	17	184
Pea	15	44	0	17	251
Carman					
Corn–soybean Int.	28	19	14	18	23/80
Pea–canola Int.	21	19	14	18	3/242
Canola	112	20	13	18	8
Corn	69	18	16	17	23
Soybean	19	19	14	18	80

Note: Barley–pea Int., barley–pea intercropping; pea–canola Int., pea–canola intercropping. Pea, faba bean, barley–pea intercropping, and faba bean–barley mix received small amount of N from the compound P fertilizer.

yellow field pea (cv. CDC Inca), canola (cv. PV 200 CL), and oat (cv. CDC Arborg) monocrops, where the intercrops received 0%, 25%, or 50% of their recommended monocrop N rate and monocrops received their full recommendation of N, except pea which received zero N. Although pea crops did not receive a direct application of N fertilizer, it still received a small percentage on N indirectly from the P compound. This resulted in six intercrop and three monocrop treatments. The experiment design was a randomized complete block design with four replications, totaling 36 plots for each site-year. The Swift Current site was located in the Brown soil zone and Melfort was in the Black soil zone. The plot size was 4×8 m^2 and seeded with a no-till Fabro Hoe Drill seeder with 25 cm row spacing. The seeding rates were 125, 200, and 300 live seeds m^{-2} for pea, canola, and oat monocrops, respectively. The seeding rates of pea–canola and pea–oat intercrops were 2/3 of the recommended seed rate of peas and ½ of the recommended seed rate of canola and oats. Intercrops were seeded in mixed rows. Peas was inoculated at the time of seeding. All fertilizers were applied in a single pass at seeding. Pesticides, fungicides, and desiccants (pre-seeding and post-seeding) were applied in intercrops and monocrops as required. Crops were harvested in August, with dates varying by crop, and crop residue was left on the soil surface after harvest. Grains from the intercrop were separated.

Study 2. Cereal and oilseed intercropping with different legume crop cultivars

The 5-year (2018–2022) intercropping study was conducted at three locations spanning three provinces: Swift Current, Saskatchewan; Lethbridge, Alberta; and Carman, Manitoba. The intercrops were presented as a phase of a 4-year crop rotation. All experimental locations except for Carman were established in 2018. The sites are located among two varying regions. Lethbridge and Swift Current are located in the southern Prairies, and Carman is located in the Red River Valley region. The soil was classified as Dark Brown Chernozem at Lethbridge, Orthic Brown Chernozem at Swift Current, and Hochfeld Black Chernozem at Carman. Lethbridge has a clay loam soil texture, while Carman has a sandy loam soil texture, and Swift Current has a loam soil texture.

The intercropping and monocropping at each location were as follows. At Swift Current and Lethbridge, intercropping included faba bean–malt barley and malt barley–field pea, and monocropping included faba bean, pea, and malt barley. In Carman, intercropping included corn–soybean and pea–canola, and monocropping included corn, soybean, and canola. The treatments were arranged using a randomized complete block design with four replicates. The plot sizes within each of the three locations were as follows. Swift Current: 14 m × 4 m; Lethbridge: 15 m × 4 m; and Carman: 14 m × 4 m. Fertilizer was side-banded at each location with the exception of Carman in 2019 and Lethbridge in 2018–2019, where fertilizer was broadcasted. Four types of fertilizer were applied at each location with differing N, phosphorus, potassium, and sulfur ratios. Different fertilizer rates were applied based on the crop being planted, the preceding crop, and soil test recommendations (Table 1). Pea, faba bean, barley–pea intercropping, and faba bean–barley mix received a small amount of N from the compound P fertilizer. Additionally, the average seeding rate for each crop at each location over the 5-year experiment period is summarized in Table 1. Herbicides, fungicides, and insecticides were selectively sprayed when needed. Herbicides were applied multiple times in a given year of the experiment: pre-seed burnoff, pre-emergence burnoff, and in-season. The amount of herbicide application for each crop was recorded alongside the number of passes required to spray the herbicide. Fungicide input was split into two applications, while insecticide input was limited to only one application. The amount of pesticide applied differed at each location and for each crop. All pesticide application rates were recorded in grams of active ingredient per hectare. Crop yield was recorded each year as moisture-corrected grain yield in kilogram per hectare.

Economic analysis

For economic analysis, 12-year average (2012–2023) input (i.e., seed and fertilizers) and output (i.e., grains) prices were used to quantify total production cost, gross revenue, and NR for the intercrops and monocrops. Seed or fertilizer costs were calculated as the product of application rates by corresponding average prices. Pesticide prices for each year were not readily available; therefore, pesticide costs based on product of prices by rates were not possible. We used a different approach to obtain 12-year average pesticide costs. Pesticide prices were assembled by calling pesticide suppliers in 2021. We multiplied those prices and the actual pesticide rates in the experiment to determine pesticide costs ha^{-1} for each crop in 2021. Saskatchewan Crop Planning Guides (Saskatchewan Agriculture 2012–2023) reports the historical pesticide costs for each crop. The estimated provincial pesticide costs for each crop were used to develop pesticide cost ratios between years, and then these ratios and the actual experimental pesticide costs in 2021 were utilized to calculate experimental pesticide costs in other years. For example, the pesticide costs for canola in 2020 and 2021 from the Saskatchewan Crop Planning Guides were $167 and $196 ha^{-1}, respectively. The ratio of these two costs was 85%. This ratio was multiplied by the actual pesticide cost from the experiment in 2021 to obtain the pesticide cost for canola in 2020. The actual pesticide costs for canola in 2019 were calculated by the provincial pesticide cost ratio between 2019 and 2020 and the actual costs in 2020. We developed similar ratios between years and continued estimating pesticide costs in other years to obtain an average 2012–2023 pesticide cost. Pesticide costs for the other crops were calculated in a similar fashion.

Similarly, field machinery operational (i.e., seeding, fertilizer and herbicide applications, and harvesting) costs were determined for each crop using the field activity data collected from the experimental sites and the farm machinery values (Saskatchewan Agriculture 2021). The machinery costs for each year were then adjusted based on an index developed using farm machinery operation costs for each crop reported in the 2012–2023 Saskatchewan Crop Planning Guide (Saskatchewan Agriculture 2012–2023). Pesticide and machinery costs for the intercropping treatments were calculated in the same fashion from the experimental data but using the indices developed based on the average of two crops from the 2012–2023 Saskatchewan Crop Planning Guides (Saskatchewan Agriculture 2012–2023). Seed cost (seed price × seed rate), fertilizer cost, land investment cost, and miscellaneous costs from 2012 to 2023 were added to the pesticide and machinery costs to calculate the average total crop cost (TC) from 2012 to 2023.

The main source of seed prices was the crop planning guides from Saskatchewan (Saskatchewan Agriculture 2012–2023). If the data were not available from Saskatchewan, the Manitoba seed prices from 2012 to 2023 (Manitoba Agriculture 2012–2023) were used as substitutes. Only 2015–2023 prices were used for soybean and corn, as there was no market price data recorded for the earlier years.

The TC of N, phosphorus, potassium, and sulfur fertilizers was calculated and added to the rest of the costs. The cost of fertilizers was calculated as the production of application rates by the corresponding average fertilizer nutrient prices from 2012 to 2023. The crop planning guide was also used to get a 12-year average price for each fertilizer nutrient: N, phosphorus, potassium, and sulfur (Saskatchewan Agriculture 2012–2023).

Intercrop and monocrop plots were harvested with a plot harvester at maturity. Harvested grains from intercrop plots were separated into individual crops manually using a Clipper seed cleaner. Grain weight and grain moisture were recorded to calculate grain yield per hectare. The estimated cost of separating grains was $0.05 CAD per kilogram, and the TC was calculated by multiplying the cost with the total yield of the intercrop. The information for intercrop operating costs was retrieved from Hickseeds through personal communication (https://hickseeds.com). We assume that all farm machinery works were operated by farmers and no custom work costs were included. Crop insurance, utilities, and property taxes were not included in the TC for each rotation. No allowance was made for interest costs related to land equity.

To compare the monetary aspects of intercropping, three criteria were used. First, the NR from intercropping and monocropping were compared. The NR analysis included all inputs used in field operations, from pre-seeding to harvest. All values were expressed in CAD $ ha^{-1} for each crop and intercrop. NR was defined as the income remaining after paying for all monetary costs (i.e., seed, fertilizer, chemicals for weed and disease controls, fuel and oil, repairs, transportation, land taxes, and interest costs on variable inputs), land investment costs, and ownership costs on machinery and buildings (depreciation, interest on investment, insurance, and housing), and labour. TC was defined as all monetary costs as indicated above associated with production of crops. The return for the entire intercrop provided a financial perspective to compare within different intercrops and with their monocropping systems.

Secondly, gross income stability using the coefficient of variation (CV = standard deviation/mean × 100) was assessed. The CV allows for a relative comparison of income stability by indicating the extent of variability in income in relation to its mean. A lower CV indicates more stable income, while a higher CV suggests greater variability. This metric was chosen because it accounts for differences in average income levels, enabling a consistent assessment of income stability across different cropping systems and locations.

Finally, N application costs by each crop were compared. The N fertilizer application rates were recorded for each crop

Table 2. Mean grain yields, total cost (TC), and net return (NR) of pea, canola, and oat monocrops and their intercrops (pea–canola and pea–oat) with 0%, 25%, and 50% of recommended nitrogen rates of canola and oat at Swift Current, SK during 2021–2022.

	2021			2022			Across years		
Treatments	Yield (kg ha^{-1})	TC ($ ha^{-1})	NR ($ ha^{-1})	Yield (kg ha^{-1})	TC ($ ha^{-1})	NR ($ ha^{-1})	Yield (kg ha^{-1})	TC ($/ha^{-1})	NR ($ ha^{-1})
Pea	1183	495^{g}	−140^{a}	2252	474^{e}	202^{b}	1718	484^{d}	31^{ab}
Canola	1092	677^{d}	−109^{a}	1638	728^{a}	124^{b}	1365	703^{ab}	7^{ab}
Oat	1251	422^{h}	−147^{a}	3743	425^{f}	399^{a}	2497	423^{e}	126^{a}
Pea–canola 0 N	842/149	691^{c}	−361^{cde}	1891/73	664^{c}	−59^{c}	1367/111	677^{b}	−210^{b}
Pea–canola 25% N	765/186	718^{b}	−392de	1835/124	693^{b}	−78^{c}	1300/155	705^{ab}	−235^{b}
Pea–canola 50% N	616/274	751^{a}	−424^{e}	1722/137	724^{a}	−136^{c}	1169/206	737^{a}	−280^{b}
Pea–oat 0 N	207/828	504^{g}	−260^{b}	596/2377	588^{d}	113^{b}	402/1603	546^{c}	−73^{ab}
Pea–oat 25% N	103/893	518^{f}	−290^{bc}	512/2492	606^{d}	97^{b}	308/1693	562^{c}	−97^{ab}
Pea–oat 50% N	92/941	543^{e}	−308^{bcd}	499/2812	644^{c}	125^{b}	296/1877	593^{c}	−92^{ab}
P value	–	<0.001	<0.001	–	<0.001	<0.001	–	<0.001	0.002

Note: In the yield columns for intercrops, the first value is for the first crop and the second value for the second crop. Means followed by the same letter in a column are not statistically significant ($P > 0.05$).

per year. The amounts applied reflect the different requirements of various crops, influenced by factors such as N removal of the target yield, amounts of soil mineral N, soil type, and the crops contained in the intercropping systems. The differences in N fertilizer costs were used to evaluate the differences between intercrop or monocrop systems, especially when the NRs are not statistically significant between the two systems. When two cropping systems show that their NRs are not different, emphasis is placed on the system that resulted in applying less N fertilizer rates and therefore lower N application costs.

Statistical analysis

Data on TCs and NRs for intercrops and monocrops were square root transformed to satisfy the model assumptions of normality, and then they were analyzed at each location and each year separately and across years, and also across locations and years using the mixed model procedure with the "*nlme*" R statistical package. Intercropping treatments were considered fixed factors because they were deliberately chosen for the specific interest of the study, and replicates were considered random factors because they were assigned randomly in replicates in the model. Treatment means were compared with least square means using the "*lsmeans*" and "multcompview" R packages when the *F* test was significant ($P < 0.05$).

Results and discussion

Study 1. Canola and oat intercropping with peas using varying levels of N fertilizer

Swift current

Annual mean grain yields, TCs, and NRs for pea, canola, and oat monocrops and the intercrops are presented in Table 2. NRs were negative in 2021. The negative NRs result from lower gross revenue, which could be due to drought-caused yield reduction in 2021. Precipitation in Swift Current during the growing season (May, June, and July) in 2021 was only 104.4 mm, while for the same period in 2022 and the long-term average were 179.3 and 188.4 mm, respectively (Liu et al. 2025; Table 2). The NRs for the pea–canola intercrops (at all N rates) were significantly lower than that of pea and canola monocrops in 2021, demonstrating no financial advantage for the intercrops. Similarly, pea–oat intercrops had NRs significantly lower than pea and oat monocrops in 2021. Li et al. (2023) identified that intercrops generally produced a lower grain yield than the higher-yielding monocrops. The drought conditions in 2021 could limit any potential yield advantages of intercrops due to the increased competition for soil moisture (Liu et al. 2025).

Oat generated higher NRs than peas and canola in 2022. However, the three monocrops showed statistically similar NRs across the years. The NRs of pea–canola intercropping in 2022 were lower than pea or canola monocrops. However, the NRs of pea–oat intercrops were similar to the NR of the pea monocrop. This indicated a greater suitability of pea–oat intercrops over pea–canola intercrops in 2022 in terms of NRs. Averaged across years, both pea–canola and pea–oat treatments, regardless of N application, had similar NR as compared to pea, canola, and oat monocrops. This suggests that the benefit of pea–oat intercropping over pea–canola intercropping was only visible in a normal year, as in 2022, but not in a droughted year (i.e., 2021) and across years. These results are consistent with Liu et al. (2025), which report better productivity of pea–oat intercrops over pea–canola intercrops at Swift Current. Moreover, pea–canola or pea–oat intercrops with their varying levels of N applications were statistically similar, suggesting that intercrops without N fertilizer application can provide similar monetary returns compared to the treatments where N was applied at this location with lower seasonal precipitation. Baily-Elkin et al. (2022) found variable NRs for pea–oat intercrops, such as an increased NR under weedy situations but a decreased NR under low weed pressure in Carman, MB. The results obtained here indicate that overall, pea–oat intercrops with varying levels of N applica-

Table 3. Coefficients of variation (%) of gross revenue of monocrops and their intercrops in Swift Current, Melfort, and across sites (study 1) and in Swift Current, Lethbridge and Carman (study 2).

Treatments	Swift Current	Melfort	Across sites	Lethbridge	Carman
Study 1					
Pea	37	36	38	–	–
Canola	22	59	51	–	–
Oat	54	28	43	–	–
Pea–canola 0 N	35	48	57	–	–
Pea–canola 25% N	35	50	60	–	–
Pea–canola 50% N	32	53	60	–	–
Pea–oat 0 N	53	34	49	–	–
Pea–oat 25% N	55	36	52	–	–
Pea–oat 50% N	57	38	52	–	–
Study 2					
Fababean–malt barley	26	–	–	34	–
Malt barley–pea	21	–	–	28	–
Malt barley	29	–	–	49	–
Fababean	21	–	–	46	–
Pea	15	–	–	33	–
Corn–soybean	–	–	–	–	11
Pea–canola	–	–	–	–	27
Soybean	–	–	–	–	25
Corn	–	–	–	–	12
Canola	–	–	–	–	33

tion can partly maintain monetary benefits similar to those of one of the monocrops under normal precipitation conditions. The results further indicate that additional N application did not improve NRs for intercrops. This could be due to adverse intercrop competition for resources other than the availability of N. In general, below normal precipitation causes lower availability of N fertilizers to crops (Peoples et al. 2009), resulting in no observable effects of N fertilization (Liu et al. 2025). A previous study reported that additional N fertilizer did not increase the productivity of peas or mustard in the intercrop (Waterer et al. 1994). Hauggaard-Nielsen et al. (2008) found that the benefits of cereal–legume intercropping are higher without N fertilizer inputs, as increasing N fertilizer rates tended to decrease pea yield in pea–oat (Neugschwandtner and Kaul 2015) and pea–canola intercrops (Malhi 2012).

Averaged gross income variability over 2021 to 2022 measured by CV was similar for the pea–canola intercrop and peas monocrop (35% vs. 37%); however, pea–canola CV was higher than the canola monocrop (35% vs. 22%) (Table 3). The pea–oat CV was higher than the peas monocrop (53% vs. 37%) but similar to the oats monocrop (53% vs. 54%). The CV comparisons indicate that intercropping had similar or higher income variability (Table 3).

Further, the N application for both intercrops, pea–canola and pea–oat, at 0 N was 4.4 kg ha^{-1}, compared to 85 and 54 kg ha^{-1} in the canola and oats monocrops, respectively (Table 4). This resulted in, on average, a 93.7% reduction in N application when intercropped (Table 4). This lower N application rate led to a cost difference of 110$ ha^{-1}, with the monocrop, on average, costing 118$ ha^{-1} and the intercrop costing 8$ ha^{-1}. The lower N requirements of intercrops directly resulted in reduced input costs associated with N applications. By reducing N rates, intercropping can reduce the environmental impacts of N application, such as greenhouse gas emissions.

Melfort

Annual mean grain yields, TCs, and NRs for pea, canola, and oat monocrops and the intercrops in Melfort are presented in Table 5. Both peas (37$ ha^{-1}) and oats (176$ ha^{-1}) had significantly higher NRs than canola (−337$ ha^{-1}) in 2021 (Table 5). However, canola (749$ ha^{-1}) in 2022 showed a higher NR than pea (271$ ha^{-1}). Canola performed poorly in 2021 due to the drought conditions but had a more typical yield in 2022. NRs for both pea–canola and pea–oat intercrops were negative and statistically similar for varying levels of N application in 2021. Again, the low precipitation during the growing season in 2021 totaled at 69.2 mm while 2022 had received a total of 203.8 mm. Additionally, the long-term norm was 173.9 mm, meaning the negative NR's was not only due to drought conditions in 2021, but the above normal precipitation in 2022 (Liu et al. 2025; Table 2). Furthermore, the results suggest no improvement for intercrops that received N fertilizer. However, pea–oat intercrops with 0 N and 25% N showed significantly higher NRs than any pea–canola intercrop and also had statistically similar NRs with pea monocrops in 2021. This suggests higher financial suitability of pea–oat intercrops with 0 N and 25% N than pea–canola intercrops in 2021 at this location. Additionally, the NRs for the pea–canola intercrops were negative and statis-

Table 4. The average nitrogen rate (kg ha^{-1}) and the cost associated ($ ha^{-1}) in intercropping and monocropping across varying crop combinations and years in Studies 1 and 2.

		N use kg ha^{-1}			N cost $ ha^{-1}		
	Crop	Intercrop	Monocrop	% change in N use	Intercrop	Monocrop	Cost difference
Study 1							
Swift Current	Pea	–	4.4*	–	–	8	–
	Canola	–	85.0	–	–	145	–
	Oat	–	54.0	–	–	92	–
	Pea–canola 0 N	4.4	–	–	8	–	–
	Pea–canola 25%N	21.3	–	–	36	–	–
	Pea–canola 50%N	42.5	–	–	73	–	–
	Pea–oat 0 N	4.4	–	–	8	–	–
	Pea–oat 25%N	13.5	–	–	23	–	–
	Pea–oat 50%N	27.0	–	–	46	–	–
Melfort	+	–	4.4∗	–	–	8	–
	Canola	–	100.5	–	–	172	–
	Oat	–	57.0	–	–	97	–
	Pea–canola 0 N	4.4	–	–	8	–	–
	Pea–canola 25%N	25.2	–	–	43	–	–
	Pea–canola 50%N	50.3	–	–	86	–	–
	Pea–oat 0 N	4.4	–	–	8	–	–
	Pea–oat 25%N	14.3	–	–	24	–	–
	Pea–oat 50%N	28.5	–	–	49	–	–
Study 2							
Swift Current	Barley	12.8	63.7	79.9	18.2	91.1	72.9
Lethbridge	Barley	14.7	76.8	80.9	21.0	109.8	88.8
Carman	Corn	27.8	60.2	53.8	39.7	86.1	46.4
	Canola	21.6	115.5	81.3	30.8	185.2	154.4

*N from the compound P fertilizer.

Table 5. Mean grain yields, total cost (TC), and net return (NR) of pea, canola, and oat monocrops and their intercrops (pea–canola and pea–oat) with 0%, 25%, and 50% of recommended nitrogen rates of canola and oat at Melfort, SK during 2021–2022.

	2021			2022			Across years		
Treatment	Yield (kg ha^{-1})	TC ($ ha^{-1})	NR ($ ha^{-1})	Yield (kg ha^{-1})	TC ($ ha^{-1})	NR ($ ha^{-1})	Yield (kg ha^{-1})	TC ($/ha^{-1})	NR ($ ha^{-1})
Pea	1917	539^{f}	37^{ab}	2630	518^{d}	271^{b}	2274	528^{d}	154
Canola	855	781^{b}	−337^{d}	2909	763^{bc}	749^{a}	1882	772^{ab}	206
Oat	2956	474^{g}	176^{a}	4716	467^{d}	571^{ab}	3836	471^{e}	373
Pea–canola 0 N	1076/361	752^{c}	−241^{cd}	2498/1104	784^{ab}	539^{ab}	1787/733	768^{b}	149
Pea–canola 25% N	804/540	789^{b}	−268^{d}	2201/1421	814^{ab}	585^{ab}	1503/981	802^{ab}	159
Pea–canola 50% N	420/718	829^{a}	−329^{d}	1422/1699	825^{a}	485^{ab}	921/1209	827^{a}	78
Pea–oat 0 N	540/1996	618^{e}	−17^{b}	1193/3452	711^{c}	407^{ab}	867/2724	665^{c}	195
Pea–oat 25% N	454/2272	646^{d}	−10^{b}	1329/3286	725^{c}	397^{ab}	892/2779	685^{c}	194
Pea–oat 50% N	317/2127	657^{d}	−94^{bc}	1051/3898	765^{bc}	408^{ab}	684/3013	711^{c}	157
P value	–	<0.001	<0.001	–	<0.001	0.052	–	<0.001	0.847

Note: In the yield columns for intercrops, the first value is for the first crop and the second value for the second crop. Means followed by the same letter in a column are not statistically significant ($P > 0.05$).

tically similar to canola (−337$ ha^{-1}) monocrops but were significantly lower than pea (37$ ha^{-1}) monocrops in 2021. The pea–oat intercrops had similar NRs to pea monocrops but less than oat (176$ ha^{-1}). In contrast, NRs for pea–canola and pea–oat intercrops with different levels of N were positive, and they were statistically similar in 2022 and also across years. This implies that N addition did not improve NRs for the intercrops even in the condition when water is not limited. Both pea–canola and pea–oat intercrops with varying N treatments had similar NRs with their respective monocrops. This also indicates that pea–oat intercrops performed better than pea–canola intercrops under dry situations such as in 2021, whereas both pea–canola and pea–oat intercrops equally performed similarly to their respective monocrops in terms of NRs in 2022 or when data are combined across years.

Table 6. Mean grain yields, total cost (TC), and net return (NR) of pea, canola, and oat monocrops and their intercrops (pea–canola and pea–oat) with 0%, 25%, and 50% of recommended nitrogen rates of canola and oat, across locations in 2021 and 2022, and across locations and years.

	Across sites 2021			Across sites 2022			Across sites and years		
Treatments	Yield (kg ha^{-1})	TC (\$ ha^{-1})	NR (\$ ha^{-1})	Yield (kg ha^{-1})	TC (\$ ha^{-1})	NR (\$ ha^{-1})	Yield (kg ha^{-1})	TC (\$/ha^{-1})	NR (\$ ha^{-1})
Pea	1550	517^{cd}	-52^{ab}	2441	496^{d}	236	1996	506^{c}	92
Canola	974	729^{a}	-223^{bcd}	2274	746^{ab}	436	1624	737^{a}	107
Oat	2104	448^{d}	15^{a}	4230	446^{d}	485	3167	447^{c}	250
Pea–canola 0 N	959/255	721^{a}	-301^{cd}	2195/589	724^{abc}	240	1577/422	723^{a}	−31
Pea–canola 25% N	785/363	754^{a}	-330^{cd}	2018/773	753^{ab}	254	1401/568	753^{a}	−38
Pea–canola 50% N	518/496	790^{a}	-377^{d}	1572/918	775^{a}	174	1045/707	782^{a}	−101
Pea–oat 0 N	374/1412	561^{bc}	-138^{abc}	895/2915	650^{c}	260	634/2163	605^{b}	61
Pea–oat 25% N	279/1583	582^{bc}	-150^{abc}	921/2889	665^{bc}	247	600/2236	623^{b}	48
Pea–oat 50% N	205/1534	600^{b}	-201^{bcd}	775/3355	704^{abc}	266	490/2445	652^{b}	33
P value	–	<0.001	<0.001	–	<0.001	0.328	–	<0.001	0.152

Note: In the yield columns for intercrops, the first value is for the first crop and the second value for the second crop. Means followed by the same lower letter in a column are not statistically significant ($P > 0.05$).

Average gross income variability over 2021 to 2022 was lower for the pea–canola intercrop than for the canola monocrop (48% vs. 59%) but higher than for the peas monocrop (48% vs. 36%) (Table 3). The CV was higher for the pea–oat intercrop than the oats monocrop (34% vs. 28%) but lower than the peas monocrop (34% vs. 36%) (Table 3). The CV comparisons suggest that although intercropping treatments provided similar NRs to monocrops across all years, they can provide less income variability compared to some monocrops like canola or peas, leading to improved risk management.

Additionally, intercropping significantly reduced N fertilizer purchase and application costs. While N addition did not improve NRs for the intercrops, the N application rate for both the intercrops, pea–canola and pea–oat, was 4.4 kg ha^{-1} at the 0 N rate, compared to 100 and 57 kg ha^{-1} in the canola and oats monocrop, respectively, resulting in, on average, a 94% reduction in N application when intercropped (Table 4). This lower N application led to a cost difference of 126\$ ha^{-1}, with the monocrop on average costing 135\$ ha^{-1} and the intercrop costing 8\$ ha^{-1}. Intercropping reduced fertilizer N input costs and provided similar NRs to monocrops in 2022 and across years but different results in 2021, a dry year. These findings suggest that intercrops could provide small financial returns since they have similar NRs to the monocrops but have better income stability. However, these returns would depend on site-specific factors such as climate as seen between 2021 and 2022.

Across locations and years

Annual mean grain yields, TCs, and NRs for pea, canola, and oat monocrops and the intercrops across sites and years are presented in Table 6. Across locations, oat (15\$ ha^{-1}) had higher NRs than canola (−223\$ ha^{-1}) in 2021 (Table 6). Across locations in 2022 and all years, monocrops showed statistically similar NRs. Both pea–canola and pea–oat intercrops had negative NRs, and were statistically similar across locations in 2021, except the NRs for pea–canola at 50% N were lower than pea–oat at 0 N or 25% N. The negative NRs in 2021 for both the pea–canola and pea–oat intercrops can be explained by low grain yields (Liu et al. 2025), which generated low gross revenue. No significant differences among N rates for both intercrops imply that neither the pea–canola or pea–oat intercrop gained a financial advantage from receiving higher N rates, regardless of weather conditions. Both pea–canola and pea–oat intercrops showed non-significant differences in NRs in 2022 and across sites and all years. This suggests that both pea–canola and pea–oat intercrops with different N treatments and monocrops performed equally across sites in 2022 and when averaged across sites and all years. Contrary to our results, some studies have shown that intercropping may produce more grain yields per hectare and therefore higher returns than monocrops (Huss et al. 2022; Li et al. 2023).

The pea–canola and pea–oat intercrops had different levels of competition. The pea and oat competition was stronger than the pea and canola competition (Liu et al. 2025). This resulted in a higher portion of pea crops in pea–canola intercrops compared to pea–oat intercrops (Liu et al. 2025). This lead to a greater amount of N mineralization during the non-growing season which most likely contributed to the greater levels of water-extractable organic carbon in pea–canola intercrops than pea–oat intercrops (Liu et al. 2025). The pea–canola and pea–oat intercrops did not have significant benefits of water-extractable dissolved N over their respective monocrops (Liu et al. 2025). Since it was short-term, the N benefits from the pea were minimal, thus, long-term research should be done to find the potential (Liu et al. 2025). In pea–oat intercrops there was high quality and quantity of straw which could be the reason for higher overall production of water-extractable organic carbon compared to its component crops (Liu et al. 2025). In contrast, the pea–canola intercrop either had equal or lower water-extractable organic carbon compared to its component crops (Liu et al. 2025). The competition within the intercrops could have contributed to a

Table 7. Mean grain yields (averaged across 4 years) of monocrops and intercrops in Swift Current, Lethbridge, and Carman.

	Grain yield (kg ha^{-1})		
Treatment	Swift Current	Lethbridge	Carman
Fababean	1310	692	–
Malt barley	3343	2546	–
Pea	2594	1436	–
Malt barley–pea	2698/558	1737/387	–
Fababean–malt barley	2574/86	1929/63	–
Canola	–	–	1014
Corn	–	–	8174
Soybean	–	–	1690
Canola–pea	–	–	116/1750
Corn–soybean	–	–	4836/586

Note: In the yield columns for intercrops, the first value is for the first crop and the second value for the second crop.

change in soil quality. In Swift Current from 2021 to 2022, total % of N in the soil and soil organic carbon increased by 7.14% and 10.7%, respectively, while Melfort decreased in those soil properties (Liu et al. 2025; Table 1).

Overall, the results demonstrated that N addition had no monetary benefits for both pea–canola and pea–oat intercrops across sites and years but variation was greater. For example, when analyzed across sites pea–canola intercrop CVs were higher than those of monocrops, pea (57% vs. 38%) or canola (57% vs. 51%). Similarly, pea–oat intercrop CVs were higher than those of monocrops, peas (49% vs. 38%) or oats (49% vs. 43%) (Table 3). In terms of N application and costs; however, intercrop treatments used significantly less N as compared to canola or oats monocrops. The N application for both the intercrops, pea–canola and pea–oat, at 0 N treatments was 4.4 kg ha^{-1}, compared to 93 and 56 kg ha^{-1} in the monocrops canola and oat, respectively, resulting in, on average, a 94% reduction in N rates when intercropped (Table 4). This lower N application led to a cost difference of 119$ ha^{-1}, with the monocrop on average costing 127$ ha^{-1} and the intercrop costing 8$ ha^{-1}.

Study 2. Cereal and oilseed intercropping with different legume crop cultivars

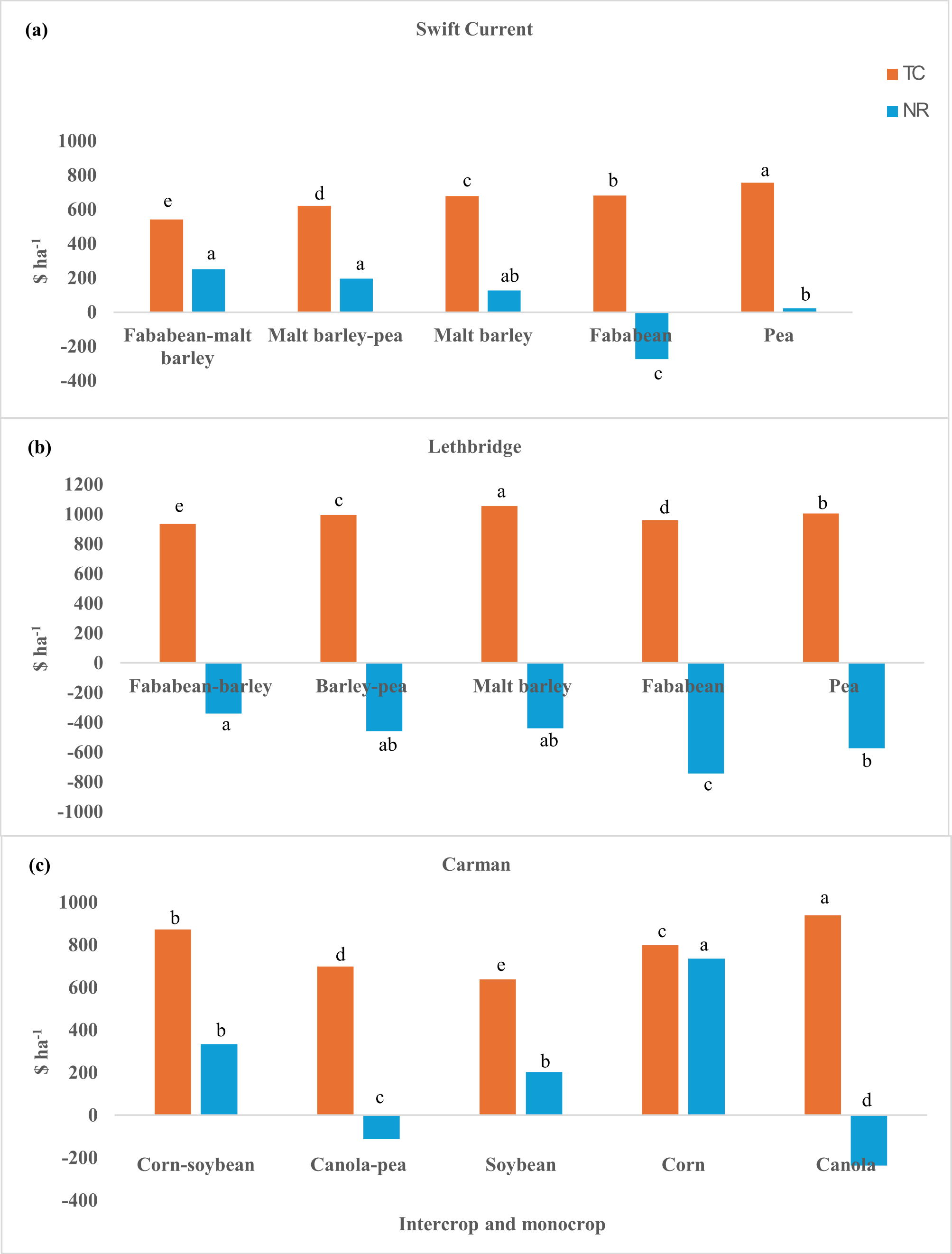
Swift current

Annual mean grain yields, TCs, and NRs are presented in Table 7 and Fig. 1*a*. The NR from faba bean–malt barley intercrop showed a positive NR of 247$ ha^{-1}, while monocrops faba bean and malt barley showed lower NRs of −275 and 127$ ha^{-1}, respectively. Statistically, intercropping faba bean–malt barley showed similar results to monocrop malt barley, while monocrop faba bean displayed significant loss (Fig. 1*a*). Averaged gross income variability over 2018–2021 measured by CV was lower for the faba bean–malt barley than barley monocrop (26% vs. 29%), indicating that faba bean–malt barley intercropping treatments not only had higher NRs but also lower income variability (Table 3). The second intercropping system tested, malt barley–field pea, had a positive NR of 195$ ha^{-1}, which was similar to their respective malt barley monocrops. However, average gross income variability was lower for the malt barley–field pea than barley monocrop (21% vs. 29%) but higher than the pea monocrop (21% vs. 15%) (Table 3). Further, the N application rate for both the intercrops, faba bean–malt barley and malt barley–field pea, was 12.8 kg ha^{-1}, compared to 63.7 kg ha^{-1} in the monocrop barley, resulting in a 79.9% reduction in N application when intercropped (Table 4). This lower N application led to a cost difference of 72.9$ ha^{-1}, with the monocrop costing 91.1$ ha^{-1} and the intercrop costing 18.2$ ha^{-1}. The lower N application in intercropping directly resulted in reduced input costs associated with N application, and can reduce the environmental impacts of fertilizer N application.

Lethbridge

The results at Lethbridge indicated a negative NR for all cropping systems (Fig. 1*b*). Both intercropping, faba bean–malt barley and malt barley–field pea showed negative NRs, around −340 and −459$ ha^{-1}, respectively. The monocrops malt barley and pea performed similarly to each other and their intercrops (Fig. 1*b*), with NRs falling between −553 and −574$ ha^{-1}, respectively. Monocrop faba bean displayed the most negative NR at −744$ ha^{-1}. Although all systems resulted in negative revenues, both intercrops were more stable compared to their respective monocrops. They had lower average gross income variability measured by CV for the faba bean–malt barley versus barley monocrop (34% vs. 49%), malt barley–field pea versus malt barley (28% vs. 49%), and malt barley–field pea versus pea monocrop (28% vs. 41%) (Table 3). The N application for both intercrops, faba bean–malt barley and malt barley–field pea, was 14.7 kg ha^{-1}, significantly lower than 76.8 kg ha^{-1} applied for the monocrop barley, resulting in an 80.9% reduction in N application with intercrop (Table 4). This reduction yielded a cost difference of 88.8$ ha^{-1}, with costing 109.8$ ha^{-1} for the monocrop and 21$ ha^{-1} for the intercrop. Although intercropping

Fig. 1. Total cost (TC, orange bar) and net returns (NR, blue bar) for intercropping and monocropping across varying crop combinations at Swift Current, Lethbridge and Carman. Each panel represents the NR data for one location, displayed on *y*-axis in $ ha^{-1} with cropping systems labelled on the *x*-axis. Means followed by the same lower letter are not statistically significant ($P > 0.05$).



reduced N application and associated costs, the overall negative NRs reflect financial pressures, likely driven by drought conditions during the study period (Wen et al. 2024). These findings suggest that financial returns from intercropping depend on site-specific factors such as climate and market demand. The smaller losses in intercropping as compared to monocropping suggest a slight financial advantage in intercropping despite the overall negative outcome.

Carman

Over the 4 years of the study, corn–soybean intercrops achieved a moderately positive NR of 334$ ha^{-1}, which is statistically similar to monocrop soybean but lower than monocrop corn (Fig. 1*c*). Intercrop pea–canola showed a negative NR of $-112$$ ha^{-1}; however, it was higher than monocrop canola. Even though the monocrop corn had the highest NR, the intercrop CV for the gross revenue showed the corn–soybean was equally stable to the monocrop corn (11% vs. 12%) and higher compared to the monocrop soybean (12% vs. 25%). The intercrop pea–canola was also more stable compared with monocrop canola (27% vs. 33%) (Table 3). Further, there was a reduction in N application from 60.2 kg ha^{-1} in monocropping corn to 27.8 kg ha^{-1} in intercropping corn–soybean, a decrease of 53.8% (Table 4). This difference in N application led to a cost saving of 46.4$ ha^{-1}, with costs of 86.1$ ha^{-1} for the monocrop corn and 39.7$ ha^{-1} for the intercrop. Additionally, N application decreased from 115.5 kg ha^{-1} in the monocrop canola to 21.6 kg ha^{-1} in the intercrop pea–canola, which represents an 81.3% reduction. This reduction led to a cost difference of 154.4$ ha^{-1}, with the monocrop costing 185.2$ ha^{-1} and the intercrop pea–canola costing 30.8$ ha^{-1}.

The reduced N applications in the intercrops were due to the incorporation of N-fixing legumes. These crops form symbiotic relationships with *Rhizobium* bacteria, which fix atmospheric N into forms usable by plants. When legumes are included in intercropping systems, they reduce the need for synthetic N fertilizers by contributing biologically fixed N to the soil (Foyer et al. 2016). Additionally, non-legume crops in the system can benefit from the residual N made available, further reducing N application (Li et al. 2003).

A limitation of this study is the short duration of Study 1 and only one phase of intercrop in a 4-year crop rotation in Study 2. The drought in 2021 gave inaccurate results of what crop production could be during a normal year. A longer duration would have determined a pattern, at least a more significant interpretation of the results. Another limitation is the study not considering the “individualism of the farmers”. The cost to one farmer can be interpreted differently to another farmer. They are all unique and have different factors to consider that were not quantified in this study. Our results are not taking into account the uniqueness of individuals. Lastly, the empirical method used is appropriate, and it could be replicated from the details and descriptions provided. However, results should be taken with caution when applying to different environmental conditions.

Conclusions

The economic analysis in this study identified the trade-offs from choosing specific alternative legume-based intercropping systems. The information generated enabled a quantification and comparison of monocropping and legume-based intercropping systems. A key insight was that under the right conditions, intercropping may provide growers with additional options to improve NRs. Intercropping performed differently with different intercrop types and growth conditions. In this study, we emphasized the monetary benefits of intercropping, analyzing intercropping for multiple site-years across western Canada.

In Swift Current, pea–canola intercrops showed no financial advantage over pea and canola monocrops in individual years or when the 2 years were combined. The pea–canola with different N rates showed statistically similar NR with pea and canola monocrops. The pea–oat intercrops were more positive with advantages over monocrops in the wetter 2022. In Melfort, reduced N fertilizer pea–oat intercrops (0 N and 25% N) showed significantly higher NRs than any pea–canola intercrops and also had statistically similar NRs with pea monocrops in 2021. This indicated a higher financial suitability of pea–oat intercrops under water limited conditions. N addition did not improve NRs for pea–canola or pea–oat intercrops at Melfort even when water was not limited. These results confirm that intercropping can significantly reduce costs compared to monocrops. Improved monetary returns of intercrops was further supported by the experimental data from both Swift Current and Lethbridge where faba bean–malt barley and malt barley–field pea intercropping treatments not only had similar or higher NRs than monocrops but also overall lower income variability.

The Carman study provided the opportunity to test intercropping for both cool season and warm season crops in the same experiment. The cool season combination, canola and pea, had a higher NR than monocrop canola and was also more stable than canola grown alone. The corn–soybean intercrop performed statistically similar to monocrop soybean but lower than monocrop corn. The corn–soybean income variability was similar to the monocrop corn but lower than the monocrop soybean. Because these benefits were achieved at a reduced N fertilizer application rate, they point to both financial and environmental advantages.

The results revealed a reduction in N fertilizer application did not lower financial returns, which highlights the potential of improved resource efficiency from intercropping. The savings observed here not only reduced input costs but also minimize environmental impacts. Monetary returns varied by location, with intercropping generally reducing losses or outperforming less profitable monocrops. However, there is still more to learn about how intercropping affects the monetary returns of cropping systems in the region; our results emphasize the need to tailor cropping systems to specific environmental and financial contexts. Further research should explore the financial outcomes of intercrops with low N usage and longer duration of studies. There is a need for better understanding of advantages from more efficient resource use, profitability under varying climatic conditions, levels of input and output prices, and longer term agronomic effects.

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Data availability

The datasets during and/or analyzed during the current study are available from the corresponding authors on reasonable request. Code availability, not applicable.

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The authors declare no competing interests.

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