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Assessing crop productivity, grain quality, and soil labile carbon and nitrogen in pea-based intercrops under low nitrogen input

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Abstract

Pea-based intercrops provide nitrogen (N) benefits and often improve land productivity through functional diversification. However, their impact on grain quality and soil health remains unclear. We conducted a 2-year (2021 and 2022) intercrop study at Swift Current and Melfort, Saskatchewan, assessing productivity, grain quality, and soil water-extractable organic carbon (WEOC) and water-extractable dissolved N (WEDN). Nine treatments included pea–oat (PO) intercrops with three N rates (0, 1/4, and 1/2 of full recommended N rate for oat monocrop), pea–canola (PC) intercrops with three N rates (0, 1/4, and 1/2 of full recommended N rate for canola monocrop), and three monocrops (pea, oat, and canola). Pea monocrop received no N fertilizer, while oat and canola monocrops received the full recommended N rate. In intercrops, pea was seeded at 2/3 and the companion crop at 1/2 of their recommended rates. PO intercrops consistently produced higher energy-based yields than PC intercrops. Intercrops outperformed monocrops at Melfort but not at Swift Current. Intercropping reduced canola protein content by 6–9% and oat protein content by 6–8%, compared to monocrops. PO intercrops increased WEOC level by 5%–9% compared to monocrops. PC intercrops resulted in 10% higher WEDN than PO intercrops, attributed to a higher pea plant stand in PC. Nitrogen fertilizer rates in intercrops did not affect yields or soil labile C and N. The results showed that applying N fertilizers to pea-based intercrops did not improve productivity, but seeding rate ratio in intercrops should be finetuned based on crop competitiveness to improve overall performance.

Key words: grain protein, energy-based yield, land equivalent ratio, oat plumpness, soil health

Introduction

Pea crops play an important role in diversifying the dominant cereal-oilseed cropping systems in the Canadian prairies (Knight 2012). One of the most significant benefits of including peas in rotations is the reduced nitrogen (N) fertilizer requirement in subsequent cereal and oilseed crops, due to the N benefits from pea residue (St. Luce et al. 2015; Liu et al. 2019*b*). The yield benefits of the subsequent cereal and oilseeds crops following peas are well documented (St. Luce et al. 2015; Liu et al. 2019*a*, 2020). In addition to pea monocropping, peas are extensively used in intercropping systems (e.g., Chapagain and Riseman 2014; Neugschwandtner and Kaul 2015; Dowling et al. 2021), which involve growing two or more crop species simultaneously in the same field (Vandermeer 1989). Intercropping pea with relatively rigid and upright crops, such as oat or canola, can reduce lodging in pea (Kontturi et al. 2011) while providing N to companion crops (Chapagain and Riseman 2014), creating mutual benefits.

Intercropping enhances functional biodiversity, generally leading to higher overall productivity. A meta-analysis indicated that intercropping produces more yield per unit of land than monocrops (Li et al. 2020). The yield benefits of intercropping are particularly evident in legume–cereal and legume–oilseed intercrops, which show greater yield increases per unit of land than monocrops, as a result of N benefits provided by legumes. Studies showed that yields increase up to 32% in pea–barley (Chapagain and Riseman 2014), 11% in pea–oat (PO) (Dordas et al. 2012), 34% in pea–wheat (Ghaley et al. 2005), and 56% in pea–canola intercrops (Malhi 2012). These yield increases are attributed to improved pest, weed, and insect controls (Lithourgidis et al. 2011), reduced lodging (Hauggaard-Nielsen and Jensen 2001; Ghaley et al. 2005), and improved resource use efficiency (Fletcher et al. 2016), particularly under stressful environments. However, compared to the most productive monocrops, intercrops may have a small reduction in grain or calorie yield (Li et al. 2023), suggesting some drawbacks of intercropping. Grains of component crops in intercrops differ in both calorie and protein content. Standardizing grain yield into energy- and protein-based metrics enables meaningful comparisons in intercrop studies, as these metrics serve as key indicator of carbon and N, two essential factors in cropping system studies. Consequently, energy- and protein-based yields provide partial insights into carbon and N cycling.

Nitrogen fertilizer input affects the crop performance of legume-based intercrops, as the application of N fertilizer can reduce biological N fixation and complicate N availability. Hauggaard-Nielsen and Jensen (2001) found that the benefits of cereal–legume intercropping were most pronounced without N fertilizer input. Increasing N fertilizer rates tended to decrease pea yield and land equivalent ratio (LER) in PO (Neugschwandtner and Kaul 2015) and pea–canola (PC) intercrops (Malhi 2012). Additionally, higher fertilizer rates increased the proportion of cereals in legume–cereal intercrops (Neugschwandtner and Kaul 2015).

Nitrogen fertilization in intercrops not only affects yield but also grain quality. At the same N fertilizer rate, oat protein levels were higher in PO intercrops than in oat monocrops (Dordas et al. 2012; Neugschwandtner and Kaul 2015). In organic cropping systems, cereal grain protein content in pea-based intercrops was higher than in cereal monocrops (Lauk and Lauk 2008; Chapagain and Riseman 2014). In addition, crop competition may lead to varied pea densities in intercrops, and cereal grain protein levels increased with higher pea plant density in pea–cereal intercrops (Dordas et al. 2012). The effects of PO intercrops on oat grain quality are not well documented in the conventional systems; however, oat groat percentage in oat monocrops increased with higher N fertilizer rates (May et al. 2020). For pea–oilseed intercrops, a literature review showed inconsistent effects of intercropping on the oil and protein contents of oilseeds compared to monocrops (Dowling et al. 2021), likely due to differences in varieties, growth environments, and management practices including N fertilizer rates. The impact of pea-based intercrops on the grain quality of non-legume crops receiving different N rates remains unknown, necessitating the need to optimize fertilizer rates to balance yield and grain quality.

Legume crop residues in intercrops accumulate more N compared to non-legume crop residues, affecting nutrient cycling and soil health. Studies showed that legume–maize intercrops increased soil C and N compared to maize monocrop (Cong et al. 2015). Chapagain and Riseman (2014) reported that pea–barley intercrops increased straw biomass C by 10% compared to barley monocrops. High biomass returns of straw with different quality from intercrops potentially alter soil C and N pools. Although long-term studies indicated that soil dissolved organic C and N levels were notably greater in intercrops compared to monocrops (Yang et al. 2024), the effects of pea-based intercrops on soil readily available C and N are still not well understood, particularly in the short term.

Enhancing crop diversification is a key strategy for building resilience to biotic and abiotic stress (Ochieng et al. 2020). Intercropping provides additional pathways for diversification, where crops might experience greater variability due to competition and trait plasticity. The performance of intercrops can vary with intercrop type, N application rate, and growth conditions. As previously noted, the majority of intercrop studies predominantly emphasize productivity, with comparatively less attention given to grain quality and short-term soil health. To adopt pea-based intercrop practices effectively, it is essential to understand the impact of pea-based intercrops on grain quality and soil health, in addition to yield. To address this gap, we conducted a 2-year study in the semi-arid and subhumid zones, Saskatchewan, Canada. The objectives of this study were to determine the responses of yield, grain quality, and soil water-extractable organic C (WEOC) and water-extractable dissolved N (WEDN) to (1) intercrop types (e.g., PO and PC), (2) cropping systems (e.g., intercrops vs. their respective monocrops), and (3) N fertilizer rates in intercrops. We hypothesized that intercrops would outperform monocrops in yield, grain quality, and soil WEOC and WEDN.

Table 1. Baseline soil chemical properties in the 0–15 cm soil depth at Swift Current and Melfort, 2021 and 2022.

	Swift Current		Melfort	
	2021	2022	2021	2022
NH_4^+–N (mg N kg^{-1})	3.34	3.19	11.77	6.59
NO_3^-–N (mg N kg^{-1})	4.14	2.74	11.23	6.75
PO_4^{-3}– P (mg P kg^{-1})	16.17	10.41	6.47	5.16
K (mg K kg^{-1})	266.3	299.5	223.0	278.0
Soil total N (%)	0.14	0.15	0.44	0.39
Soil organic carbon (%)	1.40	1.55	4.96	4.72
Soil pH	7.1	7.3	6.7	6.0

Materials and methods

Site description

A 2-year (2021 and 2022) intercrop study was conducted at Agriculture and Agri-Food Canada's Swift Current Research and Development Centre (50°16N; 107°46W) and Melfort Research Farm (52°49N; 104°35W), Saskatchewan, Canada. The soil at Swift Current site is classified as a Swinton Orthic Brown Chernozem with a silt loam texture and the soil at Melfort is an Orthic Black Chernozem with a silt clay loam texture. This study was carried out in a different field each year. The baseline soil chemical properties prior to seeding are given in Table 1. The Melfort site is located in the subhumid region while the Swift Current site is located in the semi-arid region. The precipitation during growing seasons and long-term averages are provided in Table 2.

Experimental design

Two types of intercrops, including PO and PC intercrops, were tested. Each intercrop received three N rates: 0, 1/4, and 1/2 of recommended N rate for the associated non-legume crops. In addition, pea, oat, and canola monocrops were included. Pea monocrop received no N fertilizer while oat monocrop and canola monocrop received the full recommended N rate. This resulted in six intercrop treatments and three monocrop treatments. All treatments were arranged in

Table 2. Precipitation during growing seasons (May–August) compared to long-term norms (1981–2010) at Swift Current and Melfort.

	Precipitation (mm) at Swift Current			Precipitation (mm) Melfort		
	2021	2022	Long-term norms	2021	2022	Long-term norms
May	35.9	51.2	51.2	31.4	90.8	42.9
June	29.6	37.7	77.1	37.6	78.1	54.3
July	38.9	90.4	60.1	0.2	34.9	76.7
August	55.7	7.5	47.4	69.3	36.5	52.4
Total	160.1	186.8	235.8	138.5	240.3	226.3

a randomized complete block design with four blocks, totaling 36 plots for each site-year.

Crop management

This trial was established on wheat stubbles at both sites each year to provide a comparable background. Crops were planted using a no-till plot seeder from early to mid May, with a row spacing of 25 cm for all crops. The crop cultivars were CDC Arborg oat (*Avena sativa* cv), Clearfield PV 200 Canola (*Brassica napus* cv), and CDC Inca yellow field pea (*Pisum sativum* cv). The seeding rates were 125, 200, and 300 live seeds m^{-2} for pea, canola, and oat monocrops, respectively. In the intercrops, pea was designated as the main crop and seeded at 2/3 of the recommended monocrop seeding rate, and the non-legume crop was designated as the support crop and seeded at 1/2 of the recommended monocrop seeding rate. Seeding depths were approximately 4.0 cm for pea, 3.0 cm for oat, 2.0 cm for canola, 3.0 cm for PO intercrop, and 3.0 cm for PC intercrop, depending on soil moisture conditions. Intercrops were seeded in mixed-rows. In a low N input intercropping system, pea is more competitive than canola. Crops were harvested in August with date varying by crop, and crop residues were left on the soil surface after harvest.

Pea was inoculated with commercial *Rhizobium* inoculants (e.g., granular TagTeam at a rate of 3.7 kg ha^{-1} at Swift Current and liquid Cell-Tech® at a rate of 25 mL per 10 kg of pea seeds at Melfort). No synthetic chemical N fertilizer was applied to the pea monocrop, while the oat and canola monocrops received the full recommended N fertilizer rate based on target grain N removal. Target grain N removal is 55 kg N ha^{-1} for oat and 85 kg N ha^{-1} for canola at Swift Current, and 60 kg N ha^{-1} for oat and 115 kg N ha^{-1} for canola at Melfort. Preseeding soil N (0–60 cm depth) was 43 kg ha^{-1} at Swift Current in 2021, 39 kg ha^{-1} at Swift Current in 2022, 55 kg ha^{-1} at Melfort in 2021, and 59 kg ha^{-1} at Melfort in 2022. All plots received a phosphorus fertilizer rate of 20 kg P_2O_5 ha^{-1} as monoammonium phosphate fertilizer, which was side-banded 3 cm from a seed row at a depth of 7 cm. No potassium fertilizer was applied due to high soil potassium levels in the study region. All fertilizers were applied in a single pass with seeding.

For weed control, a pre-seed application of glyphosate (900 g a.e. ha^{-1}) was implemented across the entire experimental fields annually. During growing seasons, Solo (20 g a.i. ha^{-1}) and Assure II (47 g a.i. ha^{-1}) were used in pea, canola, and PC intercrops, and MCPA (198 g a.i. ha^{-1}) in PO intercrop to kill brassicas when needed. Buctril M (560 g a.i. ha^{-1}) was applied to the oat monocrop when necessary.

Plant and soil sampling and analysis

At maturity, the center six rows from each 12-row plot were harvested using a plot combine to determine grain yield. Grains from intercrops were separated. All crop grains were cleaned and dried at 60 °C to a consistent weight. Grain yields of pea, canola, and oat are reported at moisture levels of 16.1%, 10.1%, and 13.6%, respectively.

The N content of peas was determined using an elemental analyzer (vario MICRO cube, Elementar, UK), after being finely ground through a 1 mm sieve. Pea protein content was estimated by multiplying N content by a coefficient of 6.25. The protein content of oat and canola was measured using the near infrared spectroscopy method.

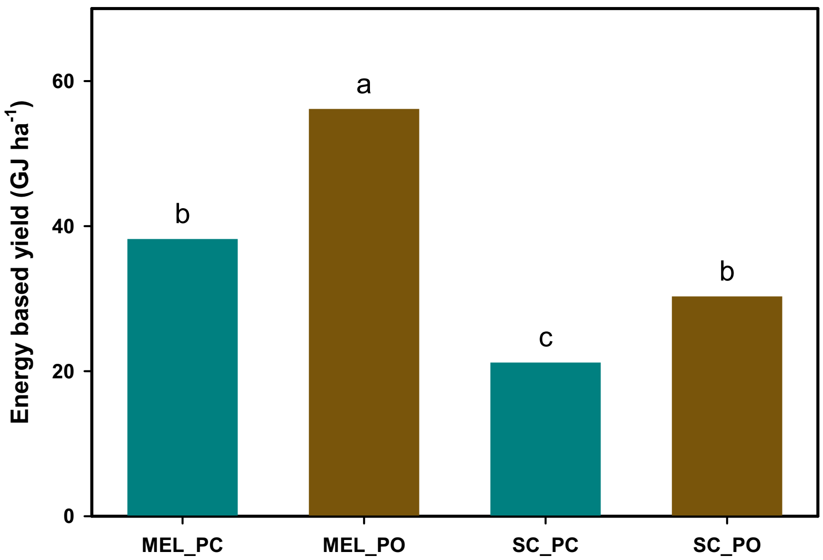
Groat percentage was determined by dehulling 50 g of oat and calculating the weight of hull-less kernels as a percentage of the total seed weight (hull and groat combined). Oat plumpness was determined by shaking 100 g of clean oat grains over a stand shaker with 5.5/64 × 3/4 inch slotted screen 30 times. The portion remaining on the screen was reported as the plumpness of oat.

To assess treatment effects on labile soil C and N, prior to seeding in the following spring, three soil cores (2 cm i.d.) were extracted to a depth of 15 cm and pooled to form one composite sample per plot. Fresh soil samples were sieved through a 2 mm screen to determine WEOC and WEDN using the method described by Chantigny et al. (2008). In this method, 30 mL of 5 mmol/L $CaCl_2$ was added to 15 g of air-dry soil. The suspension was stirred gently for 1 min with a glass rod to make a homogeneous slurry and then filtered using a 0.4 μm polycarbonate filter through a vacuum filtration apparatus to allow filtrate to be collected into a glass vial. The filtrate was stored at −20 °C, and then thawed prior to analysis. Filtrate was analyzed for WEOC and WEDN concentration by combustion using non-dispersive infrared detection with a Shimadzu TOC-VCPN analyzer (Shimadzu Corporation, Kyoto, Japan). The WEOC and WEDN measured in this study may be considered the labile, microbially bioavailable portion of soil C and N in field soils (Issah et al. 2021).

Data processing and statistical analysis

To compare yields among rotations that include crops with different yield potentials, a unified metric is required (Sanford et al. 2021). Accordingly, we standardized yields by

Fig. 1. Effects of intercrop type and study sites on energy-based yield. Mel, Melfort site; SC, Swift Current site; PC, pea–canola intercrop, and PO, pea–oat intercrop.



converting the grain yield of each crop to energy-based yield and protein-based yield. Energy-based yield was calculated based on grain yield and energy content of grains, with energy contents of 14.5, 20.7, and 16.1 MJ kg^{-1} for pea, canola, and oat, respectively (FAO 2024). Protein-based yield was calculated based on yield and protein content of grains.

LER of PO intercrop was calculated using the following equation:

$$LER = \frac{Y_{\text{intercrop}-\text{pea}}}{Y_{\text{monocrop}-\text{pea}}} + \frac{Y_{\text{intercrop}-\text{oat}}}{Y_{\text{monocrop}-\text{oat}}}$$

where $Y_{\text{intercrop - pea}}$ is the yield of pea in the PO intercrop, $Y_{\text{intercrop - oat}}$ is the yield of oat in the PO intercrop, $Y_{\text{monocrop - pea}}$ is the yield of pea in the pea monocrop, and $Y_{\text{monocrop - oat}}$ is the yield of oat in the oat monocrop. LER of PC intercrop was calculated similarly.

Data were analyzed using the PROC MIXED model in SAS (SAS Institute Inc. 2023). We consider year and block random factors; allowing for pooling of data collected over 2 years together with block for analyses. For variables of energy-based yield, protein-based yield, pea protein content, WEOC, WEDN, and LER, data were analyzed considering site (Melfort and Swift Current), intercrop type (PC and PO intercrops), and N rate (0, 1/4, and 1/2 recommended N rates) fixed factors and the new year-block combination a random factor.

To compare the differences between the intercrop and associated monocrops, we selected only the intercrop that received the 0 N rate, as the preliminary analysis indicated no difference among N rates. For this analysis, site (Melfort and Swift Current) and crops (intercrop receiving the 0 N rate, pea, and associated non-legume component monocrop) were considered fixed factors and the new-block combination a random factor.

For the analysis of oat quality (oat groat percentage, plumpness percentage, and oat protein content) and canola quality (protein and oil content) data, site (Melfort and Swift Current) and crop management (monocrops, and intercrops receiving 0, 1/4, and 1/2 N rates) were considered fixed factors and year-block combination a random factor.

For each analysis, the validity of model assumptions (i.e., normality and homogeneous variance) was verified by examining the residuals. Appropriate transformations were applied on response variables that violated statistical assumptions and back-transformed data were reported. For significant treatment effects, mean comparisons were performed at a probability level of 0.05 and the least squares means (e.g., lsmeans) were reported.

Results

Productivity

Energy-based yield

Energy-based yield was affected by site ($P = 0.02$) and the interaction between site and intercrop type ($P = 0.05$), although it was not affected by N fertilizer rate and any interaction with N rate. The energy-based yield was 83% higher at Melfort than at Swift Current. PO intercrop produced 47% higher energy-based yield than PC intercrop at Melfort and 43% higher at Swift Current (Fig. 1).

When comparing between intercrops and their component crops, energy-based yield was not different between PC intercrop and their component crops, with a yield range of 28.9 to 33.6 GJ ha^{-1}. However, for the PO intercrop, the oat monocrop produced the highest energy-based yield, followed by the PO intercrop, with pea monocrop yielding the least at both sites (Fig. 2). At Melfort, the energy-based yield was 10% and 87% higher for the oat monocrop than for the PO intercrop and pea monocrop, respectively; at Swift Current, the energy-based yield was 27% and 61% higher for the oat

Fig. 2. Comparison of energy-based yield between pea–oat intercrop and their component crops of pea and oat at Melfort and Swift Current sites. Mel, Melfort site; SC, Swift Current site; and PO, pea–oat intercrop.

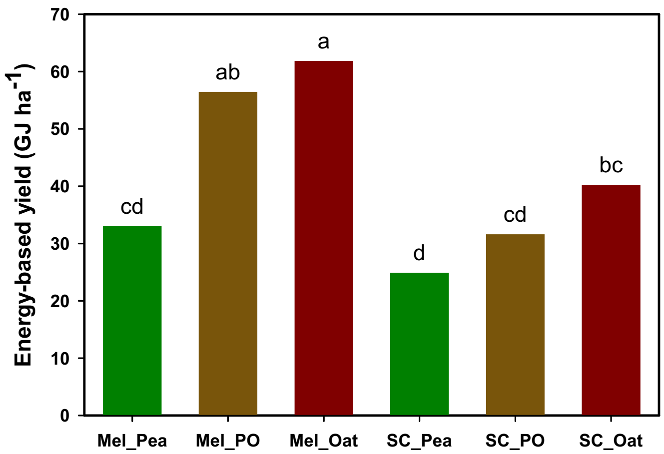
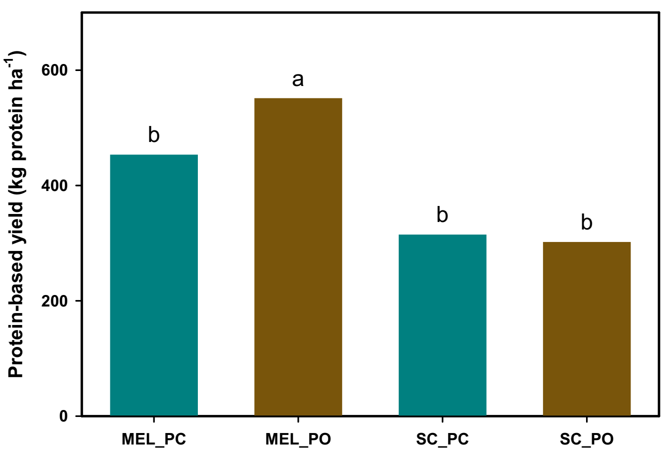


Fig. 3. Comparison of protein-based yield between pea–canola and pea–oat intercrops at two study sites. Mel, Melfort site; SC, Swift Current site; PC, pea–canola intercrop, and PO, pea–oat intercrop.

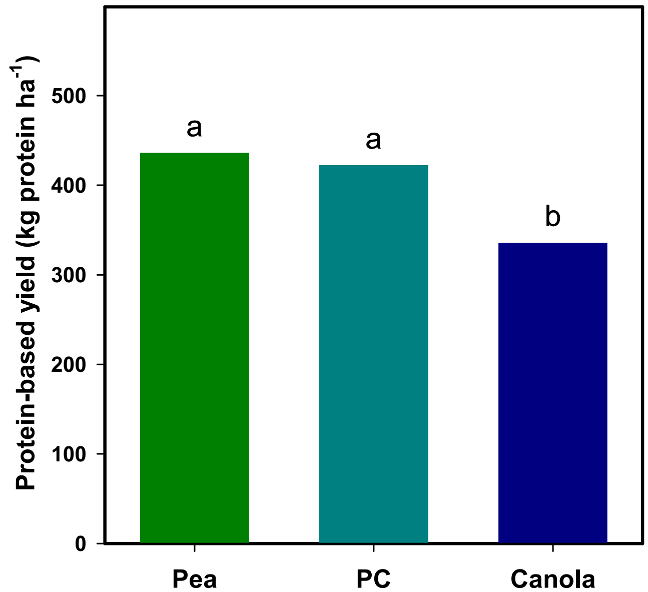


monocrop than for the PO intercrop and pea monocrop, respectively. PO intercrop produced similar energy-based yield to oat monocrop at both sites, but it produced significantly (71%) higher energy-based yield than pea at Melfort.

Protein-based yield

Similar to energy-based yield, protein-based yield was affected by site ($P = 0.03$) and the interaction between site and intercrop type ($P < 0.01$), although the N rate and any interactions that involved N rate had no significant effects on protein-based yield. The protein-based yield was 63% higher at Melfort than at Swift Current. The protein-based yield was 22% higher in the PO intercrop than in the PC intercrop at Melfort, but was not different between the two types of intercrops at Swift Current (Fig. 3).

Fig. 4. Comparison of protein-based yield between pea–canola intercrop and their component crops of pea and canola. PC, pea-canola intercrop.



When comparing protein-based yield between PO intercrops and their component crops, protein-based yields were not different, ranging from 436 to 463 kg protein ha^{-1}. However, for PC intercrops, the PC intercrop and pea monocrop produced similar protein-based yields, but the PC intercrop produced significantly (26%) higher protein-based yield than the canola monocrop ($P = 0.02$) (Fig. 4).

Land equivalent ratio

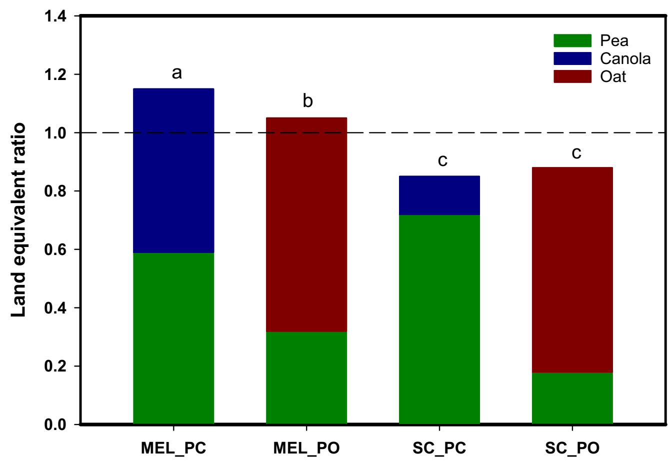
LER was affected by site ($P < 0.01$) and the interaction between site and intercrop type ($P < 0.01$). At Melfort, LERs were greater than 1 for both PC and PO intercrops, with 10% greater LER for PC (1.15) than for PO (1.05). However, at Swift Current, LERs were less than 1 for both PC and PO intercrops, with no difference between PC (0.85) and PO (0.88) intercrops (Fig. 5).

Grain quality

Canola protein and oil content

Canola protein content was affected by site ($P < 0.01$) and crop management (including monocrop, and intercrops receiving three different N rates) ($P < 0.01$), but the interaction was not significant. Canola protein content was 13% lower at the high-yielding Melfort site (22.2%) than at the low-yielding Swift Current site (25.4%). Applying N fertilizer up to half the recommended rate of monocrop canola in PC intercrops did not affect canola protein (Fig. 6A). In comparison to the canola monocrop receiving the full recommended N rate, intercropping canola with pea, receiving N rates from 0 to 1/2 of recommended rate, reduced canola protein by 6%–9% (Fig. 6A).

Fig. 5. Comparison of the land equivalent ratio (LER) between pea–canola intercrop and pea–oat intercrop across two study sites: Melfort and Swift Current. MEL, Melfort site; SC, Swift Current site; PC, pea–canola intercrop; and PO, pea–oat intercrop.



Canola oil content was not affected by crop management but was affected by study site ($P < 0.01$), with canola oil content being 12% higher at Melfort (49.4%) than at Swift Current (44.0%). The interaction effect was not statistically significant.

Oat groat percentage, plumpness percentage, protein, and beta-glucan content

Study site had no significant effect on oat groat percentage, plumpness percentage, or protein content. Without N fertilizers, intercropping oat with pea decreased oat groat percentage by 2%, compared to oat monocrop (Fig. 6B). Increasing N fertilizer rates in PO intercrops increased oat groat percentage by 1%–2% ($P < 0.01$) (Fig. 6B). PO intercrops increased oat plumpness percentage by 10%–13% compared to the oat monocrop ($P < 0.01$) (Fig. 6C), though N fertilizer application in PO had no positive effects (Fig. 6C). Intercropping oat with pea decreased oat protein content by 6%–8% ($P < 0.01$), compared to the oat monocrop (Fig. 6D), and N application did not increase oat protein content in the intercrop setting (Fig. 6D).

Pea protein content

Pea protein content was not affected by study site; however, it was 4% higher in the PO intercrop (26.0%) than in the PC intercrop (24.9%) ($P < 0.01$). Nitrogen fertilizer application in the intercrop had no effect on pea protein content. At the 0 N rate, pea protein content was 6% higher in the PO intercrop than in the PC or pea monocrop ($P < 0.01$) (Fig. 7), with similar protein content between the pea monocrop (24.6%) and the PC intercrop treatments (24.8%).

WEOC and dissolved nitrogen

WEOC in the 0–15 cm soil layer was affected by study site ($P < 0.01$) but not by N fertilizer rate. WEOC was 148% higher at Melfort (143.9 μg g^{-1}) than at Swift Current (58.1 μg g^{-1}). Intercrop type (PO vs. PC) had no effects on WEOC. When comparing WEOC between PC intercrop and its component monocrops, at Melfort, the PC intercrop (135.0 μg g^{-1}) decreased WEOC by 12% and 2% compared with the canola monocrop (152.7 μg g^{-1}) and pea monocrop (137.6 μg g^{-1}), respectively; however, at Swift Current, the PC intercrop did not affect WEOC compared to its component monocrops (Fig. 8A). In comparison, the PO intercrop (105.3 μg g^{-1}) increased WEOC by 5% and 8% compared to the oat monocrop (99.9 μg g^{-1}) and pea monocrop (96.9 μg g^{-1}) ($P = 0.04$), respectively (Fig. 9A).

WEDN in the 0–15 cm soil depth was affected by study site ($P < 0.01$) but not by N fertilizer rate. WEDN was 101% higher at Melfort (14.1 μg g^{-1}) than at Swift Current (7.0 μg g^{-1}). WEDN was also affected by intercrop type ($P < 0.01$) and was 10% higher for the PC intercrop (11.0 μg g^{-1}) than for the PO intercrop (10.0 μg g^{-1}). When comparing WEDN between PC and its component monocrops, at Melfort, the PC intercrop (13.8 μg g^{-1}) decreased WEDN by 17% compared to the canola monocrop (16.6 μg g^{-1}) and by 7% compared to the pea monocrop (14.9 μg g^{-1}); however, at Swift Current, the PC intercrop did not affect WEDN compared to its component monocrops (Fig. 8B). In comparison, the PO intercrop (9.3 μg g^{-1}) had similar WEDN to the oat monocrop (9.3 μg g^{-1}) but decreased WEDN by 8% compared to the pea monocrop (10.2 μg g^{-1}) ($P < 0.01$) (Fig. 9B).

Discussion

Effects of intercropping on grain yields

Effects of intercrops on energy- and protein-based yield relative to their respective monocrops varied between the types of intercrops. A meta-analysis identified that intercrops produce a slight loss in grain or energy-based yield compared to the higher-yielding component monocrops (Li et al. 2023). In the current study, oat monocrop had the highest energy-based yield while pea monocrop had the lowest. Intercropping oat with pea offset the lower energy-based yields of pea monocropping. In comparison, pea monocrop had the highest protein-based yield while canola had the lowest. Intercropping pea with canola improved the low protein-based yields of canola. There was no difference in energy-based yield between the PC intercrop and its component crops. Likewise, the PO intercrop showed no difference in protein-based yield compared to its component crops. These outcomes are likely due to the trade-offs between grain yield (Choo-Foo 2024) and protein contents. The interactions between crops and environments are more complicated in intercrop settings due to complimentary and competition relationships among component crops; therefore, employing more than one indicator in yield assessment can improve our understandings of the benefits and drawbacks of intercrops.

Intercrop type significantly affected both energy- and protein-based yields. The greater energy-based yield in PO intercrops compared to PC intercrops was attributed to: (1) higher oat grain yield (3267 kg ha^{-1}) than canola (1714 kg

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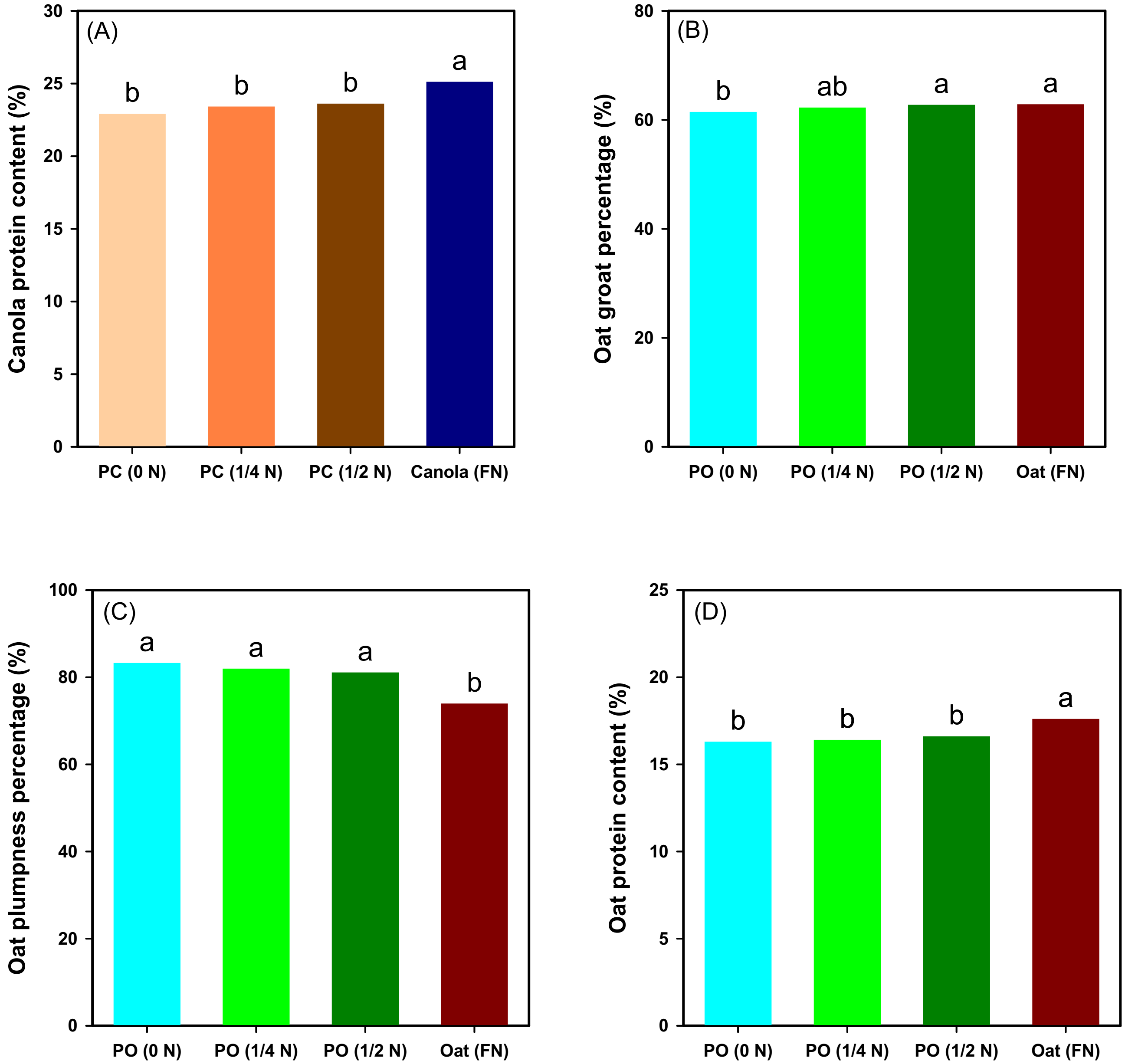
Fig. 6. Effects of intercropping on grain quality: (A) canola protein content in pea–canola intercrops, (B) oat groat percentage in pea–oat intercrops, (C) oat plumpness percentage in pea–oat intercrops, and (D) oat protein content in pea–oat intercrops, compared to their respective non-leguminous monocrops. PC, pea–canola intercrop; PO, pea–oat intercrop; 0 N, no nitrogen applied; 1/4 N, nitrogen applied at one-quarter the recommended rate for non-leguminous monocrops; 1/2 N, nitrogen applied at half the recommended rate for non-leguminous monocrops; and FN, full recommended nitrogen rate.



ha^{-1}) under the monocrop setting, and (2) a greater portion of oat than canola in their respective intercrops due to stronger competition of oat relative to canola. Crop emergence revealed that pea represented 35% of the plant stand in PO intercrops but 57% in the PC intercrop. At the subhumid Melfort site, PO intercrops had higher protein-based yield than PC intercrops due to the greater oat grain yield. Canola did not perform well in the semi-arid region; consequently, pea became the dominant crop in PC intercrops (the partial LER for pea = 0.72, the partial LER for canola = 0.18). The overwhelmingly dominant pea crop contributed to higher protein-based yield in PC, offsetting the high oat yield induced protein-based yield in PO. Consequently, protein-based yield was not different between PC and PO at Swift Current. Based on both energy- and protein-based yields, PO was much more productive than PC.

Nitrogen fertilizer rates in intercrops had no effect on energy- or protein-based yields, because N application rates in intercrops were relatively low (up to half of the recommended rate), which allows pea in intercrops to fix more N biologically. Similarly, Waterer et al. (1994) reported that additional N fertilizer did not increase the productivity of pea or mustard in the intercrop. These findings suggest that there is no need to apply for N fertilizers in pea-based intercrops if

Fig. 7. Comparison of pea protein content in pea monocrop with pea–oat and pea–canola intercrops receiving no nitrogen fertilizer. PO, pea–oat intercrop and PC, pea–canola intercrop.

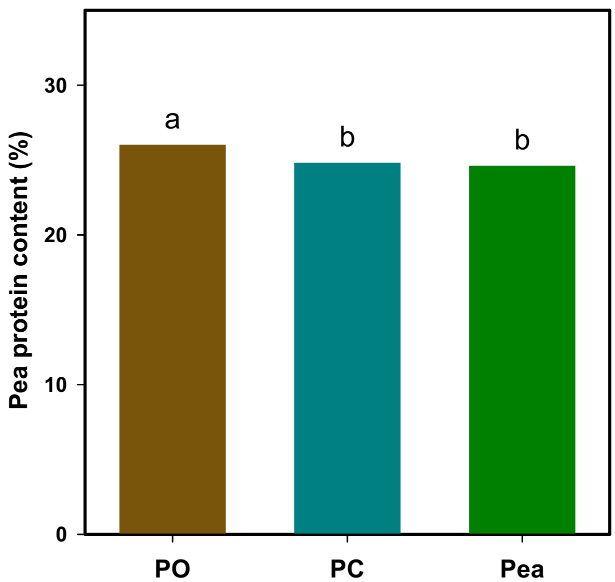


Fig. 8. Effects of intercropping pea with canola on (A) water-extractable organic carbon and (B) water-extractable dissolved nitrogen determined in the 0–15 cm soil layer in the following spring. Mel, Melfort site; SC, Swift Current site; and PC, pea–canola intercrop.

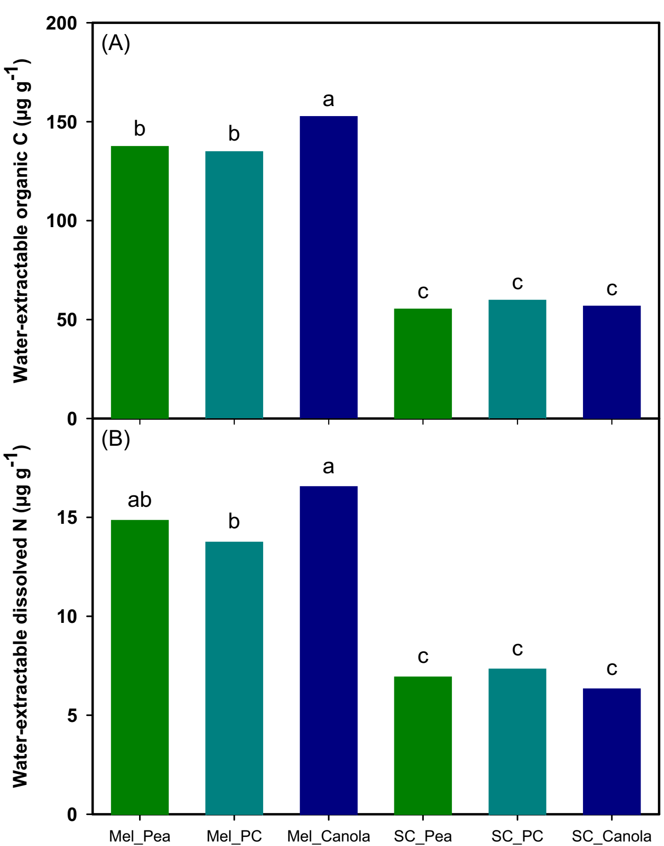
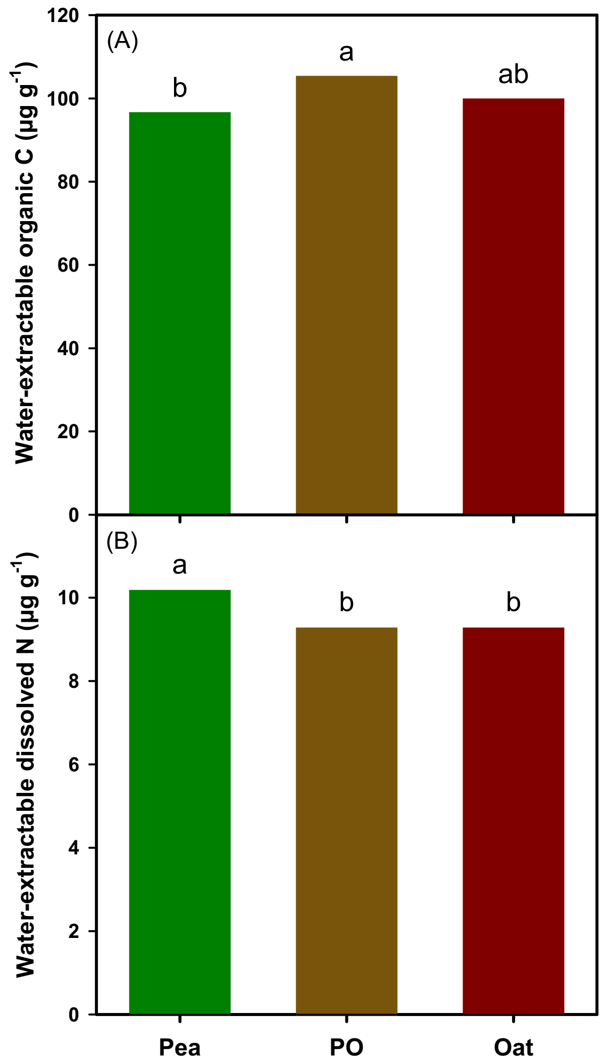


Fig. 9. Effects of intercropping pea with oat on (A) water-extractable organic carbon and (B) water-extractable dissolved nitrogen determined in the 0–15 cm soil layer in the following spring. PO, pea–oat intercrop.



productivity is the main goal. However, no N fertilizer application might compromise protein content of grains in intercrops as discussed below.

Effects of intercrops on land productivity varied, depending on the specific intercrops. Chapagain and Riseman (2014) reported that land productivity was 12%–32% higher in pea–barley intercrops than monocrops due in part to N transfer from pea to barley during growing seasons. Studies showed that intercropping normally produced more grain yields per hectare than monocrops (Huss et al. 2022; Li et al. 2023). In the current study, intercrops had a greater (5%–15%) land productivity than monocrops at the subhumid Melfort site, while they had a lower (12%–15%) land productivity at the semi-arid Swift Current site. Intercrops provide numerous benefits, but these advantages might not materialize in a semi-arid environment. At Swift Current, precipitation during the two study years was 21%–32% lower compared to the long-term average. The drought conditions in Swift Current limited any potential yield advantages of intercrops due to the increased competition for limited moisture, thus resulting in lower land productivity. At both sites, canola had a smaller partial LER than pea due to the weaker competition of canola relative to pea. Conversely, oat had a larger partial LER than pea due to the stronger competition of oat relative to pea. To balance the competition between two component crops in intercrops, the seeding rate of two component crops in the intercrop can be adjusted to help address the skewed partial LERs.

Effects of intercropping on grain quality of canola, pea, and oat

Intercropping canola with pea had no effects on canola oil content, but resulted in a 13% reduction in canola protein content, compared to the canola monocrop. The lower canola protein content in PC intercrops compared to canola monocrop contradicts our hypothesis. Low N availability is the main reason for the low canola protein content in PC intercrops. Precipitation during the three of the four study site-years was 21%–39% lower than long-term normal, leading to dry conditions. These dry conditions not only lowered soil N availability, but also severely reduced the biological N fixation of pea (Peoples et al. 2009), thus lowering N supplies in intercrops. The lower canola protein content in intercrops indicated that N fixation in the PC intercrop was not sufficient to supply adequate N to enhance canola protein content. Even adding small amounts of N fertilizers (up to half the recommended N rate) in PC intercrops had no effects on canola protein content, as applied N fertilizer reduces nodulation and biological N fixation by pea (Hubbard et al. 2023), partially offsetting the benefits of N fertilizers. In comparison, the full recommended N rate contributed to the significantly higher canola protein content in the monocrop than in the intercrops. Studies showed that N fertilizer application increased canola protein content (Zuo et al. 2016; Crittenden et al. 2024), but it might increase (Crittenden et al. 2024) or decrease (Zuo et al. 2016) oil content, depending on varieties and growth conditions.

At the Melfort site, higher background soil mineral N level (18 kg N ha^{-1} at Melfort vs. 7 kg N ha^{-1} at Swift Current), combined with greater N fertilizer input based on target yield potential (115 kg N ha^{-1} at Melfort vs. 85 kg N ha^{-1} at Swift Current), contributed to increased N availability. In addition, higher total soil N (0.42% at Melfort vs. 0.15% at Swift Current) likely resulted in greater mineral N release under more humid conditions at Melfort (189 mm vs. 173 mm of annual rainfall during the growing season). The higher N availability likely explained the 22.2% greater canola protein content at Melfort compared to at Swift Current.

Intercropping pea with oat significantly improved pea protein content compared to the pea monocrop, while intercropping pea with canola showed no effects. In PO intercrops, oat competed strongly with pea for natural resources, particularly during the reproductive growth stage. This competition created unfavorable growth conditions for pea, resulting in lower pea yield as indicated by the partial LER (Fig. 5). Stressful environments negatively affect pea yields but increase protein content as a survival mechanism (i.e., Bénézit et al. 2017), leading to greater pea protein content in the PO intercrops than in the pea monocrop. In addition, compared to oat, canola is a heavier N feeder, leading to a stronger competition for N than oat in intercrop setting. Thus, we speculated that there was more N available for pea in the PO intercrops than in the PC intercrops. This higher N availability explained the 4% higher pea protein content in PO than in PC.

Intercropping oat with pea significantly increased oat plumpness compared to the oat monocrop. Studies from a Canadian prairie showed that N fertilizer application (0–140 kg N ha^{-1}) had either no or negative effect on oat plumpness, depending on growth environment (May et al. 2020). The relatively low N fertilizer rate in PO intercrops, intended to avoid inhibiting pea biological N fixation, might contribute to higher oat plumpness. In addition, the complementary root systems of peas (taproot) and oats (fibrous) enable both crops to use available soil water effectively. This is particularly beneficial under dry conditions, where arbuscular mycorrhizal fungi in PO intercrops enhance water use efficiency (Lee et al. 2023). The resulting improved water use efficiency in intercrops can facilitate oat grain filling and increased oat plumpness percentage.

Intercropping pea with oat decreased oat protein content compared to the oat monocrop. In contrast, Lauk and Lauk (2008) reported that oat protein content was 3%–10% higher in PO intercrops than in oat monocrop without N fertilizer application. Similarly, under organic practices, Chapagain and Riseman (2014) reported barley protein content increased by 13%–28% in pea–barley intercrops compared to a barley monocrop, attributed to the biological N fixation of pea, which enhanced N availability and protein synthesis. The lower oat protein content in PO intercrops contrasts with our hypothesis, primarily due to lower N fertilizer input in intercrops (up to the half the recommended N rate) compared to that in oat monocrop (e.g., the full recommended N rate). Our results aligns with findings from studies in the Canadian prairies, which reported greater oat protein content with higher N fertilizer rates (May et al. 2004). Our findings imply that the limited N benefits provided by pea during the PO intercrop growing season were insufficient to sustain high oat protein levels.

Intercropping pea with oat negatively affected oat groat percentage compared to the oat monocrop, especially evident when no N fertilizers were applied in the PO intercrop. Studies in the Canadian prairies consistently showed that oat groat percentage increased with higher N fertilizer rates (May et al. 2004, 2020), explaining the trend of improved groat percentage in intercrops as N rates increased. The highest groat percentage in the oat monocrop treatment resulted from the highest N fertilizer rate (e.g., the full recommended rate). These findings suggest that the reduced N fertilizer application in the PO intercrop compromised certain aspects of oat quality, despite the N benefits provided by pea in PO intercrops during the intercrop season.

Effects of intercropping on water-extractable organic carbon and dissolved nitrogen

Intercrop type had no effect on WEOC, but PC intercrops resulted in 10% higher WEDN than PO intercrops. This difference in WEDN might be attributed to varying crop competitiveness within intercrops. Oat's stronger competition with pea compared to canola resulted in a higher proportion of pea crops in PC intercrops than in PO intercrops (Choo-Foo 2024), leading to greater N deposition in the rhizosphere during the growing season and more pea residues available for mineralization in the PC intercrop. The greater amount of pea residue in PC likely led to increased N mineralization during the non-growing season, explaining the greater WEDN levels in PC than in PO.

However, neither PC nor PO intercrops had apparent WEDN benefits over their respective non-legume monocrops. This suggested that soil N benefits from the pea component in intercrops were minimal in the short-term (e.g., in the year following intercrops). Studies on pulse–oilseed intercrops in western Canada showed that the soil N benefits from legume components in intercrops took longer to materialize (Reid 2022). This suggests that a longer-term study might be needed to capture the potential soil N benefits of pulse-based intercrops.

The PO intercrops increased WEOC compared to its component crops. This change in WEOC related to the PO intercrop is likely related to both straw quality and quantity. Intercropping pea with oat balanced the high-quality straw input from pea and the high-quantity straw input from oat, which may contribute to higher overall production of WEOC during microbial decomposition. In contrast, the lower quantity of pea residue in the pea monocrop and the low N content of oat straw in the oat monocrop would be factors having a negative influence on WEOC levels in both pea and oat monocrops. However, different than PO intercrops, PC intercrops showed varied responses in WEOC, with PC intercrops resulting in either equal or lower WEOC compared to its component crops. Therefore, the responses of WEOC were intercrop-specific. Similarly, Reid (2022) reported that effects of legume–oilseed intercrop on WEOC varied among sites and years.

The influence of local environmental conditions on soil C and N dynamics is evident in this study. Higher WEOC and WEDN at the Melfort site compared to the Swift Current site can be attributed to the high soil organic matter, fertility background, and subhumid weather conditions. Gregorich et al. (2006) reported that water-extractable organic matter fractions are typically higher in regions with greater precipitation. Similarly, Campbell et al. (2000) reported that crop residue decomposes more quickly in humid regions, leading to increased levels of soluble organic compounds. In contrast, limited precipitation reduced the decomposition rate of crop residues and the stabilization of soil organic matter (Maillard et al. 2018). At Swift Current, precipitation during two growing seasons was 21%–32% lower than long-term normal, likely slowing residue decomposition and resulting in no difference in WEOC and WEDN between treatments. The difference in weather and soil fertility between the two sites likely affect nodule formation and N fixation (Peoples et al. 2009; Hubbard et al. 2023), underscoring the importance of considering local environmental conditions when evaluating the effects of intercropping on soil C and N dynamics.

Nitrogen fertilizer application rates in intercrops had no significant effects on either WEOC or WEDN. This lack of N fertilizer effect could be attributed to the relatively low N fertilizer rates (up to half of the recommended rate) used in the intercrops, where the maximum rate was only half of the recommended N rates. A reduced N rate was used, because the N benefits of intercropping are more pronounced at lower N rates, allowing the legume component to contribute more significantly to N fixation. In three of the four site-years, precipitation during growing season from May to August was 21%–39% lower than the long-term normal. The lower-than-normal precipitation likely reduced the availability of N fertilizers to crops, resulting in no observable effects of N fertilization.

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There are no competing interests.

References

Bénézit, M., Biarnès, V., and Jeuffroy, M.-H. 2017. Impact of climate and diseases on pea yields: what perspectives with climate change? Oils. Fat. Crop. Lipids, **24**: D103.

Campbell, C.A., Zentner, R.P., Liang, B.C., Roloff, G., Gregorich, E.C., and Blomert, B. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan—effect of crop rotations and fertilizers. Can. J. Soil Sci. **80**: 179–192. doi:10.4141/S99-028.

Chantigny, M.H., Angers, D.A., Kaiser, K., and Kalbitz, K. 2008. Extraction and characterization of dissolved organic matter. *In* Soil sampling and methods of analysis. *Edited by* M.R. Carter and E.G. Gregorich. CRC Press, Boca Raton. pp. 649–667.

Chapagain, T., and Riseman, A. 2014. Barley–pea intercropping: effects on land productivity, carbon and nitrogen transformations. Field Crops Res. **166**: 18–25. doi:10.1016/j.fcr.2014.06.014.

Choo-Foo, K. 2024. Nitrogen acquisition of pea-oat and pea-canola intercrops and their impact on subsequent wheat crops. Master's degree thesis. University of Saskatchewan, Saskatoon, Saskatchewan.

Cong, W.-F., Hoffland, E., Li, L., Six, J., Sun, J.-H., Bao, X.-G., et al. 2015. Intercropping enhances soil carbon and nitrogen. Global Change Biol. **21**: 1715–1726. doi:10.1111/gcb.12738.

Crittenden, S., Clayton, G., Boyce, M., Deng, X., and Grant, C. 2024. Canola variety, nitrogen, phosphorus, and sulfur fertilization affect yield, quality, and fatty acid profile. Can. J. Plant Sci. **104**: 1–12. doi:10.1139/cjps-2023-0055.

Dordas, C.A., Vlachostergios, D.N., and Lithourgidis, A.S. 2012. Growth dynamics and agronomic-economic benefits of peaoat and peabarley intercrops. Crop Pasture Sci. **63**: 45–52. doi:10.1071/CP11181.

Dowling, A., Sadras, V.O, Roberts, P., Doolette, A., Zhou, Y., and Denton, M.D. 2021. Legume-oilseed intercropping in mechanised broadacre agriculture—a review. Field Crops Res. **260**. doi:10.1016/j.fcr.2020.107980.

FAO. 2024. Nutritive factors. Available from https://www.fao.org/economic/the-statistics-division-ess/publications-studies/publications/nutritive-factors/en/ [accessed 25 May 2024].

Fletcher, A.L., Kirkegaard, J.A., Peoples, M.B., Robertson, M.J., Whish, J., and Swan, A.D. 2016. Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. Crop Pasture Sci. **67**: 1252–1267. doi:10.1071/CP16211.

Ghaley, B.B., Hauggaard-Nielsen, H., Høgh-Jensen, H., and Jensen, E.S. 2005. Intercropping of wheat and pea as influenced by nitrogen fertilization. Nutr. Cycling Agroecosyst. **73**: 201–212. doi:10.1007/s10705-005-2475-9.

Gregorich, E.G., Beare, M.H., McKim, U.F., and Skjemstad, J.O. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Sci. Soc. Am. J. **70**: 975–985. doi:10.2136/sssaj2005.0116.

Hauggaard-Nielsen, H., and Jensen, E.S. 2001. Evaluating pea and barley cultivars for complementarity in intercropping at different levels of soil N availability. Field Crops Res. **72**: 185–196. doi:10.1016/S0378-4290(01)00176-9.

Hubbard, M., Thomson, M., Menun, A., May, W.E., Peng, G., and Bainard, L.D. 2023. Effects of nitrogen fertilization and a commercial arbuscular mycorrhizal fungal inoculant on root rot and agronomic production of pea and lentil crops. Front. Plant Sci. **14**. doi:10.3389/fpls.2023.1120435.

Huss, C.P., Holmes, K.D., and Blubaugh, C.K. 2022. Benefits and risks of intercropping for crop resilience and pest management. J. Econ. Entomol. **115**: 1350–1362. doi:10.1093/jee/toac045.

Issah, G., Schoenau, J., and Knight, J.D. 2021. Landscape position, sampling time, and tillage, but not legume species, affect labile carbon and nitrogen fractions in a 4-yr-old rejuvenated grazed pasture. Can. J. Soil Sci. **101**: 641–653. doi:10.1139/cjss-2021-0052.

Knight, J.D. 2012. Frequency of field pea in rotations impacts biological nitrogen fixation. Can. J. Plant Sci. **92**: 1005–1011. doi:10.4141/cjps2011-274.

Kontturi, M., Laine, A., Niskanen, M., Hurme, T., Hyövelä, M., and Peltonen-Sainio, P. 2011. Pea–oat intercrops to sustain lodging resistance and yield formation in northern European conditions. Acta Agric. Scand. B Soil Plant Sci. **61**: 612–621.

Lauk, R., and Lauk, E. 2008. Pea-oat intercrops are superior to pea-wheat and pea-barley intercrops. Acta Agric. Scand. B Soil Plant Sci. **58**: 139–144.

Lee, A., Neuberger, P., Omokanye, A., Hernandez-Ramirez, G., Kim, K., and Gorzelak, M.A. 2023. Arbuscular mycorrhizal fungi in oat-pea intercropping. Sci. Rep. **13**: 390. doi:10.1038/s41598-022-22743-7.

Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Li, H., Zhang, C., et al. 2020. Yield gain, complementarity and competitive dominance in intercropping in China: a meta-analysis of drivers of yield gain using additive partitioning. Eur. J. Agron. **113**: 125987. doi:10.1016/j.eja.2019.125987.

Li, C., Stomph, T.-J., Makowski, D., Li, H., Zhang, C., Zhang, F., and van der Werf, W. 2023. The productive performance of intercropping. Proc. Natl. Acad. Sci. **120**: e2201886120. doi:10.1073/pnas.2201886120.

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A., and Vlachostergios, D.N. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. Aust. J. Crop Sci. **5**: 396–410.

Liu, K., Bandara, M., Hamel, C., Knight, J.D., and Gan, Y. 2020. Intensifying crop rotations with pulse crops enhances system productivity and soil organic carbon in semi-arid environments. Field Crops Res. **248**: 107657. doi:10.1016/j.fcr.2019.107657.

Liu, K., Blackshaw, R.E., Johnson, E.N., Hossain, Z., Hamel, C., St-Arnaud, M., and Gan, Y. 2019a. Lentil enhances the productivity and stability of oilseed-cereal cropping systems across different environments. Eur. J. Agron. **105**: 24–31. doi:10.1016/j.eja.2019.02.005.

Liu, L., Knight, J.D., Lemke, R.L., and Farrell, R.E. 2019b. A side-by-side comparison of biological nitrogen fixation and yield of four legume crops. Plant Soil, **442**: 169–182. doi:10.1007/s11104-019-04167-x.

Maillard, É., McConkey, B.G., St. Luce, M., Angers, D.A., and Fan, J. 2018. Crop rotation, tillage system, and precipitation regime effects on soil carbon stocks over 1 to 30 years in Saskatchewan, Canada. Soil Tillage Res. **177**: 97–104. doi:10.1016/j.still.2017.12.001.

Malhi, S.S. 2012. Improving crop yield, N uptake and economic returns by intercropping barley or canola with pea. Agric. Sci. **03**: 1023–1033. doi:10.4236/as.2012.38124.

May, W.E., Brandt, S., and Hutt-Taylor, K. 2020. Response of oat grain yield and quality to nitrogen fertilizer and fungicides. Agron. J. **112**: 1021–1034. doi:10.1002/agj2.20081.

May, W.E., Mohr, R.M., Lafond, G.P., Johnston, A.M., and Stevenson, F.C. 2004. Effect of nitrogen, seeding date and cultivar on oat quality and yield in the eastern Canadian prairies. Can. J. Plant Sci. **84**: 1025–1036. doi:10.4141/P04-044.

Neugschwandtner, R.W., and Kaul, H.-P. 2015. Nitrogen uptake, use and utilization efficiency by oat–pea intercrops. Field Crops Res. **179**: 113–119. doi:10.1016/j.fcr.2015.04.018.

Ochieng, J., Kirimi, L., Ochieng, D.O., Njagi, T., Mathenge, M., Gitau, R., and Ayieko, M. 2020. Managing climate risk through crop diversification in rural Kenya. Clim. Change, **162**: 1107–1125. doi:10.1007/s10584-020-02727-0.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., et al. 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. pp. 1–17. Symbiosis.

Reid, M.A. 2022. Two pulse-oilseed intercrop combinations to enhance yield and nutrient availability in Saskatchewan. Master's degree thesis, Department of Soil Science. University of Saskatchewan, Saskatoon, Saskatchewan.

Sanford, G.R., Jackson, R.D., Booth, E.G., Hedtcke, J.L., and Picasso, V. 2021. Perenniality and diversity drive output stability and resilience in a 26-year cropping systems experiment. Field Crops Res. **263**: 108071. doi:10.1016/j.fcr.2021.108071.

SAS Institute Inc. 2023. SAS/STAT® 15.3 user's guide. SAS Institute Inc. Cary, NC.

St. Luce, M., Grant, C.A., Zebarth, B.J., Ziadi, N., O'Donovan, J.T., Blackshaw, R.E., et al. 2015. Legumes can reduce economic optimum nitrogen rates and increase yields in a wheat-canola cropping sequence in western canada. Field Crops Res. **179**: 12–25. doi:10.1016/j.fcr.2015.04.003.

Vandermeer, J.H. 1989. The ecology of intercropping. Cambridge University Press, Cambridge.

Waterer, J.G., Vessey, J.K., Stobbe, E.H., and Soper, R.J. 1994. Yield and symbiotic nitrogen fixation in a pea-mustard intercrop as influenced by N fertilizer addition. Soil Biol. Biochem. **26**: 447–453. doi:10.1016/0038-0717(94)90176-7.

Yang, Z., Zhang, Y., and Luo, G. 2024. Regulation of soil C–N–P stoichiometry by intercropping mitigates microbial resource limitations and contributes to maize productivity. Plant Soil, **498**: 21–38. doi:10.1007/s11104-023-06251-9.

Zuo, Q.S., Zhou, G.S., Yang, S.F., Yang, Y., Wu, L.R., Leng, S.H., et al. 2016. Effects of nitrogen rate and genotype on seed protein and amino acid content in canola. J. Agric. Sci. **154**: 438–455. doi:10.1017/S0021859615000210.