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Winter pea-canola intercropping: A strategy for enhanced productivity and land use efficiency

Eric R. Page[1] | **Jamie Larsen**[1] | **Sydney Meloche**[1] | **Alyssa Thibodeau**[1] | **Emma Bedal**[1] | **Meghan Moran**[2] | **Brian Caldbeck**[3]

[1]Agriculture and Agri-Food Canada, Harrow Research and Development Centre, Harrow, Ontario, Canada

[2]Ontario Ministry of Agriculture, Food and Agribusiness, Stratford, Ontario, Canada

[3]Caldbeck Consulting, Philpot, Kentucky, USA

Correspondence
Eric R. Page, Agriculture and Agri-Food Canada, Harrow Research and Development Centre, 2585 County Rd. 20, Harrow, ON, Canada, N0R 1G0.
Email: Eric.Page@agr.gc.ca

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Abstract

Winter intercropping offers a promising strategy to enhance land use efficiency and crop productivity in temperate agroecosystems. This 5-year field study evaluated the performance of winter pea (*Pisum sativum* L.)–canola (*Brassica napus* L.) intercrops (peaola) under reduced nitrogen fertilization and variable plant population densities in southwestern Ontario. Intercropping in alternate rows significantly improved pea yield, with sole pea crops averaging 1.2 Mg ha^{-1} compared to 1.8–2.4 Mg ha^{-1} in intercrops, depending on density and overwinter survival. Land equivalent ratio values ranged from 1.0 to 2.3, and transgressive overyielding index exceeded 1.0 in high-survival years, indicating that intercrops outperformed the best-yielding sole-crop. Net-effect ratios (NERs), weighted using observed spring species proportions, further revealed how winterkill-driven shifts in relative density shaped intercrop performance: high net-effect ratio weighted using observed spring species proportions values aligned with years of strong pea survival and high total spring relative density. Intercropping also altered canopy structure by elevating pea pod height from 49 cm in sole-crops to 87 cm in intercrops, enhancing light capture during canola senescence. Canola yield declined by over 40% relative to the sole-crop baseline in years of vigorous pea growth, reflecting competitive interactions, yet overall system productivity improved whenever both species survived winter and maintained adequate spring density. These findings highlight how winter intercropping can enhance land use efficiency and, in years with strong legume survival, deliver substantial yield gains through combined temporal and structural complementarity.

Abbreviations: DOY, day of year; fIPAR, fractional intercepted photosynthetically active radiation; LER, land equivalent ratio; NER, net-effect ratio; NER_{Fall}, net-effect ratio weighted using fall planted species proportions; NER_{Spring}, net-effect ratio weighted using observed spring species proportions; PAR, photosynthetically active radiation; TOI, transgressive overyielding index.

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Plain Language Summary

Intercropping, or growing two crops together, can improve land use and resource efficiency. A 5-year Ontario study tested winter pea–canola intercropping ("peaola") under reduced nitrogen and varied canola densities. When peas survived winter, land use efficiency nearly doubled versus sole-crops. Pea yields were often higher in intercrops, while canola declined in years of strong pea growth, yet overall productivity improved. Intercropping altered canopy structure: peas grew taller and captured light as canola senesced, boosting pea performance and harvestability. These advantages were supported by performance metrics showing that peaola outperformed the sole-crops in years with good pea survival. Peaola works because peas and canola use light at different times and because peas benefit from the structural support of canola. The system shows strong potential to enhance productivity in winter annual cropping, though success depends heavily on pea overwinter survival. Future work should refine management and evaluate strategies to improve consistency across years.

1 | INTRODUCTION

Winter annual cropping systems offer a range of agronomic and ecological benefits in temperate regions, including enhanced soil cover, reduced erosion, and more efficient use of the full growing season (Congreves et al., 2015; Cubins et al., 2019; Gaudin, Janovicek, et al., 2015; Gaudin, Tolhurst, et al., 2015; Larsen et al., 2018). By maintaining active crop growth through the winter months, these systems reduce nutrient leaching, reduce soil erosion, improve soil structure, and support microbial activity. In the United States and Canada, winter wheat (*Triticum aestivum* L.) is the most widely grown winter annual cash crop, covering approximately 13.5 million ha (33.3 million acres) and 0.69 million ha (1.7 million acres) of arable land, respectively, as of 2025 (StatCan, 2025; United States Department of Agriculture, NASS, 2025). In Canada, the integration of winter canola (*Brassica napus* L.) into conventional corn–soybean–winter wheat production systems is being investigated as a strategy to further diversify crop rotations and enhance system profitability (Page et al., 2021, 2024). Other winter annual crops that have shown promise across the northern Great Plains and Corn Belt include rye (*Secale cereale* L.), winter peas (*Pisum sativum* L.), camelina (*Camelina sativa* (L.) Crantz), and field pennycress (*Thlaspi arvensis* L.), each contributing uniquely to soil fertility, weed suppression, and overall system resilience (Blackshaw et al., 2010; Cubins et al., 2019; Gesch et al., 2014; Larsen et al., 2018; Tollenaar et al., 1992; Yurgel & McGee, 2025).

Extending upon the benefits of winter annual cropping systems, winter intercropping, the practice of growing two or more crops simultaneously on the same field, offers additional opportunities to enhance agroecosystem performance. While intercropping with spring annuals has already demonstrated potential to improve resource use efficiency, yield stability, and ecosystem services, particularly when component crops differ in growth habit and phenology (Bailey-Elkin et al., 2021; Mbanyele et al., 2024; Szumigalski & Van Acker, 2006, 2008), similar principles are now being applied to winter cropping systems (Blackshaw et al., 2010; Lithourgidis et al., 2011; Vályi-Nagy et al., 2024, 2023). For example, Vályi-Nagy et al. (2023) demonstrated that winter wheat–pea mixtures enhance yield stability through complementary phenology and resource use. Deep-rooted, sturdy wheat varieties supported pea growth under drought and heat stress, while winter pea contributed nitrogen and improved temporal niche differentiation; a process in which component crops differ in the timing of their growth periods, reducing the duration of direct overlap and allowing each species to access light and nutrients at different times of the season (Yu et al., 2015). These interactions boosted wheat grain weight and spikelet development, especially when sowing densities were optimized. Such findings highlight the potential of winter intercropping to enhance agroecosystem function through strategic pairing of species with contrasting growth dynamics.

A key constraint in winter annual cash cropping systems, whether managed as sole-crops or intercrops, is overwinter survival. Winterkill can significantly reduce stand density, biomass accumulation, and ultimately yield, particularly in legumes and cereals sensitive to frost, ice, and freeze–thaw cycles. For example, Strydhorst et al. (2015) reported that winter pea survival in Alberta ranged from complete winterkill to over 80% survivability, depending on site and year. Under harsh conditions, even well-emerged stands failed to persist, highlighting the narrow window for successful establishment and the importance of cultivar adaptation and timely planting. Similarly, in intercrops, Blackshaw et al. (2010) found that fall-planted Austrian winter pea and alfalfa

exhibited good overwinter survival when intercropped with winter wheat, whereas red clover suffered significant winterkill in two of three experiments. Although survival was not compared to sole-crops, these results suggest that species-specific winter hardiness may be more critical than intercropping as a system in determining overwinter success.

Management factors such as plant population density and fertility also play a critical role in determining both overwinter survival and yield in winter annual cropping systems. Unlike spring crops, where these parameters are primarily optimized for yield, winter systems require consideration of how they influence cold tolerance, root establishment, and survival through freeze–thaw cycles. This complexity is further amplified in winter intercrops, where management decisions must account for the physiological needs and competitive dynamics of multiple species. In pea-canola systems (peaola), for example, adjusting plant density can shift the balance between pea and canola, influencing biomass allocation, canopy structure, and resource capture (Mbanyele et al., 2024). Studies in spring peaola have shown that higher legume densities can improve nitrogen fixation and suppress weeds, but may also reduce oilseed yield if competition is not managed (Stubbs et al., 2025). Similarly, nitrogen fertility must be carefully calibrated: while legumes contribute biologically fixed nitrogen, excessive N inputs can favor the nonlegume partner, diminishing the benefits of intercropping. In winter systems, where nutrient uptake and root activity are seasonally constrained, the timing and form of N application may further affect overwinter survival and spring regrowth.

Despite growing interest in winter intercropping, there remains a significant knowledge gap regarding how agronomic management practices, particularly plant density and fertility, affect overwinter survival, productivity, and land use efficiency in temperate climates. To address this, we conducted a 5-year field study (2021–2025) in Southwestern Ontario, focusing on winter pea–canola intercrops. Management treatments included reduced nitrogen fertility and lowered canola seeding rates, designed to minimize competitive interactions and enhance pea performance. Key measurements included winter survival, canopy light interception, pod height distribution, yield, and three indicators of intercrop performance: land equivalent ratio (LER), the net-effect ratio (NER), and the transgressive overyielding index (TOI). The overarching goal was to enhance pea productivity within winter annual intercrop systems while contributing to more sustainable land use under variable environmental conditions.

2 | MATERIALS AND METHODS

A field trial was conducted over five growing seasons (2020–2025) at Agriculture and Agri-Food Canada's Harrow Research and Development Centre (42.03° N, −82.90° W). The soil at the site was classified as Harrow sandy loam (65% sand, 26% silt, and 9% clay), with a pH of 6.6 and 1.8% organic matter. The experiment followed a randomized complete block design with four replicates to evaluate the impact of intercropping on the productivity of winter peas. Five treatments were established using sole-crops or intercrops of the winter canola hybrid Mercedes (Rubisco Seeds) and two winter pea varieties: Windham (McPhee et al., 2007) used in 2020–2021, 2021–2022, and 2022–2023; and Goldenwood (ProGene) used in 2023–2024 and 2024–2025. The treatments were as follows: (1) winter pea sole-crop, (2) winter canola sole-crop seeded at 437,445 plants ha^{-1}, (3) winter canola sole-crop seeded at 291,630 plants ha^{-1}, (4) winter peaola with canola seeded at 437,445 plants ha^{-1} and peas seeded at their full sole-crop density, and (5) winter peaola with canola seeded at 291,630 plants ha^{-1} and peas seeded at their full sole-crop density. Sowing each species at its respective sole-crop density in the intercrop treatments resulted in a fully additive intercrop design. In all pea containing treatments, winter peas were seeded at 750,000 plants ha^{-1}. Winter peas and canola were seeded in mid-September each year, with exact dates ranging from September 9 to 17 depending on field conditions.

Prior to planting, trifluralin (Treflan Liquid emulsifiable concentrate 480 g L^{-1}) was applied at 1.1 kg a.i. ha^{-1} and incorporated twice. Winter pea seed was treated with a liquid rhizobium inoculant (XiteBio SoyRhizo, XiteBio Technologies Inc.) at 60 mL per 27 kg seed, containing two billion *Bradyrhizobium japonicum* mL^{-1}, to encourage nodulation. Experimental plots measured 2.1 m × 6 m, with plot width determined by implement geometry rather than by a fixed number of row intervals. Sole-crop plots were seeded in five rows spaced 0.38 m apart using a precision vacuum seeder (Monosem Inc.). Intercropped plots contained 10 alternating rows of winter pea and canola, spaced 0.19 m apart. This was achieved by seeding five rows of the first crop, shifting the seeder 0.19 m, and interseeding the second crop.

After seeding, a fertilizer blend of 10–20–20 (N–P_2O_5–K_2O) was broadcast across the entire experimental area at 151 kg ha^{-1}, supplying approximately 15 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1}, and 30 kg K_2O ha^{-1}. Volunteer winter cereals and grasses were controlled post-emergence with quizalofop-*p*-ethyl (Assure II, 96 g L^{-1}, AMVAC Canada ULC) at 0.05 kg a.i. ha^{-1}, along with the recommended surfactant (Sure-Mix at 0.5% v/v). In late October or early November, the plant population density of winter peas and canola was determined by counting the number of seedlings in one meter of row per plot. In spring, percent survival was assessed by recounting the same area.

As part of a deliberate strategy to reduce competitive interactions and enhance pea performance within the intercrop,

spring fertility inputs were minimized. A low-nitrogen fertilizer blend was applied to all plots to support winter pea development prior to canola bolting (i.e., late March to early April). This blend included 21–0–0–24 (ammonium sulfate) at 56 kg ha^{-1}, which provided approximately 12 kg N ha^{-1} and 13 kg S ha^{-1}; 0–46–0 (triple superphosphate) at 162 kg ha^{-1}; and 0–0–62 (potassium chloride) at 320 kg ha^{-1}, contributing roughly 198 kg K_2O ha^{-1}. The total nitrogen applied was approximately 11.8 kg N ha^{-1}, substantially lower than conventional winter canola recommendations of 80–120 kg N ha^{-1} (OMAFRA, 2017). Fractional intercepted photosynthetically active radiation (fIPAR) was measured biweekly from early April until harvest using a ceptometer (LP-80, Meter Group). The probe (81.5 cm long) was placed on the ground beneath the canopy, perpendicular to the rows, with an external sensor held above the canopy. Three readings were averaged per plot.

As winter canola approached Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie stage 86 (Lancashire et al., 1991; Weber & Bleiholder, 1990), a harvest aid application of diquat (Reglone, 240 g L^{-1}, Syngenta Canada Inc.) was applied at 0.4 kg a.i. ha^{-1} following manufacturer recommendations. Plots were harvested at physiological maturity using a small plot combine (Wintersteiger Classic Plus Combine, Wintersteiger Inc.) with factory settings for peas. In sole-cropped canola, the three middle rows (3 × 0.38 m = 1.14 m effective width) were harvested. In intercrops, the combine header was centered to capture three canola rows and three pea rows (alternate rows at 0.19 m spacing; ~1.14 m effective width), rather than using the full 1.3 m physical header width. For each species, harvested area was calculated as the number of that species' rows within the swath × 0.38 m row spacing × 6 m plot length. Grain of pea and canola was separated post-harvest, dried for at least 48 h, and weighed; yields were expressed on a per-hectare basis using the species-specific effective harvested area. Moisture content was measured using a Dickey-John grain moisture meter (GAC500 XT, TSI Instruments Ltd.), and final weights were adjusted to 8.5% moisture for canola and 14% for peas. This approach ensured that, although the physical header was 1.3 m wide, the effective yield area for each species was defined by its counted rows, preserving accuracy under alternate-row geometry.

Post-harvest soil sampling was conducted annually from 2022 to 2025, excluding the initial study year (2021). For each plot, 10 soil cores were collected from the 0- to 15-cm depth using a soil probe and combined into a single composite sample. Samples were then shipped to a commercial laboratory for extraction and quantification of nitrate-nitrogen (NO_3^--N) and ammonium-nitrogen (NH_4^+-N) (SGS Laboratories Guelph).

2.1 | Statistical analysis

Statistical analysis was performed in SAS Studio (v3.81; SAS Institute Inc.). Pea and canola data were analyzed separately using PROC MIXED. Cropping system was treated as a fixed effect and year-wise analyses were conducted; block (replication) was a random effect. The pea model included treatments with peas (Peas, Peaola, and Peaola LD); the canola model included treatments with canola (Canola, Canola LD, Peaola, and Peaola LD). Response variables were grain yield, percent winterkill, and pod height traits (lower, mid, and upper canopy). Least-squares means were compared using Tukey's Honestly Significant Difference (HSD). Model diagnostics included residual–fitted and residual–treatment plots to assess variance homogeneity, and Q–Q plots to evaluate normality of residuals.

We evaluated intercropping performance using three complementary indices: the LER, the NER, and the TOI (De Wit, 1960; Li et al., 2023; Willey & Rao, 1980). For NER, we report two variants that differ in how expected yields are weighted by species proportions: NER_{Spring} (net-effect ratio weighted using observed spring species proportions) uses observed spring proportions derived from winterkill × planted density while NER_{Fall} (net-effect ratio weighted using fall planted species proportions) uses the planned full-additive assumption (0.5/0.5). Each metric (LER, NER_{Spring}, NER_{Fall}, and TOI) was then analyzed separately by year using linear mixed models with canola plant population density (PPD) as a fixed effect and block as a random effect.

LER was calculated following the classic formulation based on partial relative yields. For a two-species intercrop, LER is defined as follows:

$$\mathrm{LER} = \frac{Y_{\mathrm{RI},1}}{Y_{\mathrm{SC},1}} + \frac{Y_{\mathrm{RI},2}}{Y_{\mathrm{SC},2}},$$

where $Y_{RI,1}$ and $Y_{RI,2}$ are yield of each crop in the intercropping system and $Y_{SC,1}$ and $Y_{SC,2}$ are the corresponding yields of the same crops in sole-cropping. An LER greater than 1 indicates a land-use advantage of intercropping over sole-cropping.

NER quantified the net effect of intercropping relative to the expected yield based on mixture proportions:

$$\mathrm{NER} = \frac{Y_{\mathrm{RI},1} + Y_{\mathrm{RI},2}}{P_1 * Y_{\mathrm{SC},1} + P_2 * Y_{\mathrm{SC},2}},$$

where P_1 and P_2 represent the proportion of each crop in the intercrop. For NER_{Fall}, P_1 and P_2 were set to 0.5 to reflect equal row allocation between winter canola and peas. For NER_{Spring}, P_1 and P_2 were set to the observed spring

species proportions derived from winterkill × planted density. Because NER is sensitive to the choice of species proportions in the expected-yield denominator, both NER variants were calculated and compared. A supplementary diagnostic figure (Figure S1) illustrates how the difference between the two estimates ($\Delta = \mathrm{NER}_{\mathrm{Spring}} - \mathrm{NER}_{\mathrm{Fall}}$) varies with realized mixture density (Spring relative density total), confirming that winter survival and composition materially influence net effect calculations.

TOI was calculated to determine whether the intercrop achieved transgressive overyielding compared to the best-performing sole-crop:

$$\mathrm{TOI} = \frac{Y_{\mathrm{RI},1} + Y_{\mathrm{RI},2}}{\max\left(Y_{\mathrm{SC},1},\ Y_{\mathrm{SC},2}\right)}.$$

TOI values greater than 1 indicate transgressive overyielding, meaning that the intercrop outperformed the most productive monoculture. TOI values less than or equal to 1 indicate no such advantage.

The fIPAR of each cropping systems were analyzed for each plot using nonlinear sigmoidal growth models fitted in SAS Studio using PROC NLIN. We modeled the rise in fIPAR through time using a candidate set of three-parameter sigmoidal functions, specifically the Logistic and Gompertz forms. For each plot-level time series, both models were fit using nonlinear least squares, and the best-supported model was selected using Akaike's information criterion corrected for small sample size. Model-selection outcomes (number of plots best fit by each model) for every cropping system and year are provided in Table S1. This approach avoided imposing symmetry a priori and allowed each canopy to be described by the curve form most consistent with the observed interceptance trajectory. The functions took the general form as follows:

$$f(x) = \frac{a}{1 + \exp\left(-\frac{(x - x_0)}{b}\right)} \quad (1)$$

for the Logistic model, and

$$f(x) = a \exp\left[-exp\left(\frac{-x - x_0}{b}\right)\right] \quad (2)$$

for the Gompertz model, where $f(x)$ is the predicted fIPAR on day of year (DOY) x, a is the asymptotic maximum canopy interceptance, x_0 is date of half-maximum fIPAR (DOY50), and b is the rate parameter controlling the steepness of canopy increase in interceptance. From the selected model for each plot, we extracted the parameters a, x_0 (DOY50), and the date of canopy closure (DOY95), defined as the DOY at which the fitted curve reached 95% of its asymptote. These plot-level estimates were then used to compute cropping-system means and to evaluate differences among systems using fixed-effect analysis of variance with Tukey's HSD for post-hoc comparisons.



FIGURE 1 Comparative inter-row canopy closure between sole-crop winter canola (A) and winter peaola (B). Photo taken on April 30, 2024.

3 | RESULTS

Winter survival of peas and canola varied across years and cropping systems (Table 1). Sole-crop peas had low winterkill in most years, except in 2022 (63.8%) and 2025 (9.6%). Intercropped systems, particularly Peaola LD, showed consistently high winterkill, reaching 95.2% in 2025 and similar levels in 2022 and 2024. Canola survival was high in all cropping systems, with Canola LD showing zero winterkill in most years. Mean temperatures from December to February in 2022 and 2025 were −3.2°C and −4.2°C, respectively, compared to milder winters in 2021 and 2024, which averaged −1.4°C and −0.1°C (Table S2). The frequency of freeze–thaw events, defined as days with minimum temperatures below −2°C and maximum temperatures above +2°C, occurred mainly from January to April, with annual totals ranging from 18 (2025) to 29 (2021–2022; Table S3). Years with frequent freeze–thaw events, such as 2024 (26 events), did not correspond to higher winterkill, whereas years with colder mean temperatures from December to February showed greater pea mortality.

Canopy light-interceptance patterns differed markedly among cropping systems, reflecting clear contrasts in both the magnitude and timing of canopy development (Table 2; Figure 1). Sole-crop peas generally reached the highest peak fIPAR (a) in most years (0.75–0.99), although the ranges overlapped with canola and in some cases (e.g., 2023) canola matched or exceeded pea. The most consistent distinction between the sole-crops was phenological: peas exhibited the latest dates of half-maximum fIPAR (DOY50) in every year ($p < 0.05$; Table S4), indicating slower but ultimately more complete canopy formation. Sole-crop canola, in contrast,

TABLE 1 Winterkill percentages across cropping systems (CS) and years (2021–2025).

Cropping system	2021		2022		2023		2024		2025	
	Peas (%)	Canola (%)	Peas (%)	Canola (%)	Peas (%)	Canola (%)	Peas (%)	Canola (%)	Peas (%)	Canola (%)
Peas	0.0		63.8		3.1		1.1b		9.6b	
Peaola	10.5	2.8	74.2	3.8	9.4	5.6	19.6a	7.0	95.2a	4.2
Peaola LD	3.0	0.0	67.8	0.0	9.4	0.0	12.6a	0.0	90.8a	2.5
Canola		1.6		11.1		0.0		3.6		8.8
Canola LD		0.0		0.0		0.0		2.5		0.0
Factor	*p*-value									
CS	0.225	0.715	0.259	0.203	0.649	0.088	0.003	0.639	<0.0001	0.305

Note: Within each year and crop (pea or canola), means followed by different letters differ significantly at $\alpha = 0.05$ (Tukey's Honestly Signifncant Difference).

TABLE 2 Cropping-system means (± SE) for peak fIPAR (*a*), date of half maximum fIPAR (DOY50), and date of canopy closure (DOY95) for each year.

Year	Cropping system	*a*	DOY50	DOY95
			mean ± SE	
2021	Canola	0.817 ± 0.020BC	92.6 ± 4.4B	126 ± 3.9
	Canola LD	0.776 ± 0.031C	96 ± 4.7AB	127 ± 2.3
	Peaola	0.936 ± 0.020A	93.9 ± 4.5B	133.5 ± 4.6
	Peaola LD	0.896 ± 0.017AB	99.5 ± 1.4AB	122.6 ± 0.4
	Winter peas	0.960 ± 0.039A	112.5 ± 2.9A	141.6 ± 8.9
2022	Canola	0.701 ± 0.038C	107.3 ± 1.8B	126.2 ± 6.1B
	Canola LD	0.739 ± 0.061BC	110.8 ± 1.6B	135.7 ± 4.9A
	Peaola	0.826 ± 0.046AB	107.6 ± 3.6B	134.0 ± 4.8A
	Peaola LD	0.829 ± 0.077AB	114.9 ± 1.4B	136.8 ± 5.1A
	Winter peas	0.916 ± 0.044A	129.3 ± 1.7A	154 ± 4.5A
2023	Canola	0.960 ± 0.048	76.2 ± 6B	153.6 ± 14.6
	Canola LD	0.956 ± 0.078	98.2 ± 9.9AB	141.6 ± 21.8
	Peaola	0.993 ± 0.051	82.2 ± 14.8B	158.8 ± 11.6
	Peaola LD	0.964 ± 0.082	93 ± 18.4AB	144 ± 24.6
	Winter peas	0.746 ± 0.075	141.5 ± 2.6A	159.2 ± 9.3
2024	Canola	0.715 ± 0.085B	98.7 ± 2B	120.3 ± 8.4
	Canola LD	0.674 ± 0.029B	103.7 ± 2.1B	131.4 ± 8.5
	Peaola	0.930 ± 0.050A	107 ± 4AB	131.4 ± 11.9
	Peaola LD	0.950 ± 0.016A	109.6 ± 3.5AB	143.1 ± 5.9
	Winter peas	0.955 ± 0.010A	117.7 ± 2.5A	134.5 ± 6.5
2025	Canola	0.859 ± 0.020B	97.8 ± 0.1B	99.6 ± 0.6B
	Canola LD	0.853 ± 0.015B	97.8 ± 0.1B	99.2 ± 0.5B
	Peaola	0.871 ± 0.009B	97.7 ± 0.1B	99 ± 0.3B
	Peaola LD	0.879 ± 0.013B	97.9 ± 0.4B	108.3 ± 4.6B
	Winter peas	0.990 ± 0.003A	106.4 ± 1.6A	133 ± 4.4A

Note: Within a given year and metric, means followed by different letters differ at $\alpha = 0.05$ (Tukey Honestly Signficant Difference).
Abbreviations: DOY, day of year; fIPAR, fractional intercepted photosynthetically active radiation.

showed earlier DOY50 values and typically lower peak fIPAR (0.70–0.96), reflecting a rapid early-season canopy rise. Intercropped systems (Peaola and Peaola LD) formed canopies that were intermediate to their component crops: they maintained relatively high peak fIPAR while shifting DOY50 earlier than sole peas and later than sole canola, consistent with significant DOY50 differences in all years. Effects on the date of canopy closure (DOY95) were more year-dependent, with significant cropping-system effects occurring in some years (e.g., 2022 and 2025) but not others (Table 2). Canola density further modulated these patterns, with the lower density system producing more variable canopy development but generally following the same seasonal trajectory as standard-density canola.

Grain yield differed markedly among cropping systems and years, reflecting patterns of overwinter survival and interaction among crops (Figure 2; Table S5; Table S6). Sole-crop peas yielded between 790 and 2853 kg ha^{-1}, with the highest yield observed in 2024 and the lowest in 2022. In contrast, sole-crop canola yields were consistently higher, ranging from 2056 to 4525 kg ha^{-1}, with peak performance in 2023. Yield stability varied across cropping systems (Figure S2): sole-crop canola produced the most consistent yields (mean: 3186–3204 kg ha^{-1}; CV: 12%–17%), while intercropped canola showed reduced yields and greater variability (mean: 2286–2660 kg ha^{-1}; CV: 24%–32%). Pea yields were more variable; notably, the pea component within the intercrop often exceeded sole-crop peas in years with favorable survival. In years when cropping system effects on pea yield were statistically significant (2021, $p = 0.009$, 2024, $p < 0.0001$; Table S5), pea component yields differed among systems, with the highest yields occurring in the intercrop treatments. In 2021, pea yields in the intercrop reached 4814 kg ha^{-1} (Peaola LD) and 3,615 kg ha^{-1} (Peaola). Although cropping systems effects were not statistically significant in 2024 ($p = 0.152$), means pea yields in the intercrop were also high, reaching 4203 kg ha^{-1} (Peaola LD) and 3248 kg ha^{-1} (Peaola). By contrast, canola yields within the intercrop ranged from 1447 to 5141 kg ha^{-1}, with the largest reductions occurring in years of vigorous pea growth, when cropping system effects on canola yield were statistically significant (2021, $p = 0.001$; 2024, $p = 0.006$; Table S6).

Spring relative density strongly shaped these yield outcomes. Across all years, higher total spring relative density was positively associated with LER (Figure 3), indicating that intercrop advantages were greatest when both species survived winter and maintained sufficient spring stand density. Conversely, years with low spring relative densities, particularly for pea, showed LER values near or below 1, reflecting limited complementarity and reduced pea contribution to system-level yield. Canola plant population density influenced canola yield but did not affect the LER (Figure 2; Table 3). In sole-crops, the lower density canola treatment (Canola LD) produced yields comparable to or greater than the standard-density treatment, and LER values were similarly unaffected by canola density. Both Peaola and Peaola LD exhibited comparable complementarity, with LER ranging from 1.0 to 1.9 for Peaola and from 1.1 to 2.3 for Peaola LD. The highest LER values occurred in 2021 and 2024, when spring relative density was high, whereas the lowest values in 2022 and 2025 coincided with severe pea winterkill and reduced spring stand density (Table 3).

TABLE 3 Land equivalent ratio (LER; mean ± 95% confidence interval [CI]) for Peaola and Peaola-LD intercrops by year.

Year	Peaola	Peaola LD
	Mean ± (95% CI)	
2021	1.93 ± (1.66, 2.20)	2.28 ± (1.55, 3.0)
2022	1.17 ± (0.23, 2.11)	0.96 ± (0.59, 1.33)
2023	1.77 ± (0.04, 3.51)	1.69 ± (0.21, 3.17)
2024	1.86 ± (1.38, 2.35)	2.01 ± (1.27, 2.76)
2025	1.06 ± (0.90, 1.23)	1.05 ± (0.88, 1.21)

Differences between NER_{Spring} and NER_{Fall} (Table S7) reflected the strong influence of winter survival on realized species proportions. Across years, NER_{Fall} tended to underestimate intercrop performance in seasons with high pea survival, whereas NER_{Spring} increased accordingly, producing positive ΔNER values that tracked increases in spring relative density (Figure S1). In high-survival years (2021 and 2024), both NER_{Spring} and NER_{Fall} exceeded 1, indicating net positive intercrop effects. By contrast, years with high pea winterkill (2022 and 2025) produced NER values close to or below 1, consistent with limited complementarity. TOI showed similar patterns, with values greater than 1 in 2021 and 2024, indicating transgressive overyielding, and values near or below 1 in years with substantial pea mortality (Figure 4).

Canopy structure at maturity influenced pod placement in both winter pea and canola systems, with notable differences among treatments (Figures 5 and 6; Tables S5 and S6). Sole-crop peas had the lowest median pod height at 49 cm, indicating a relatively short and compact canopy. In contrast, sole-crop canola systems exhibited consistently taller pod placement, with median heights of 116 cm across both Canola and Canola LD systems. Intercropping elevated pea pod height substantially. In both Peaola and Peaola LD systems, pea pods reached 87 cm, while canola pods remained tall at 113–115 cm (Figures 5 and 6). Canola density had minimal impact on pod height, as both standard and low-density canola systems maintained similar median values.

Post-harvest soil nitrogen data (2022–2025) showed substantial variation in nitrate concentrations across crop treatments, whereas ammonium concentrations remained relatively consistent (Table 4). Significant differences in nitrate

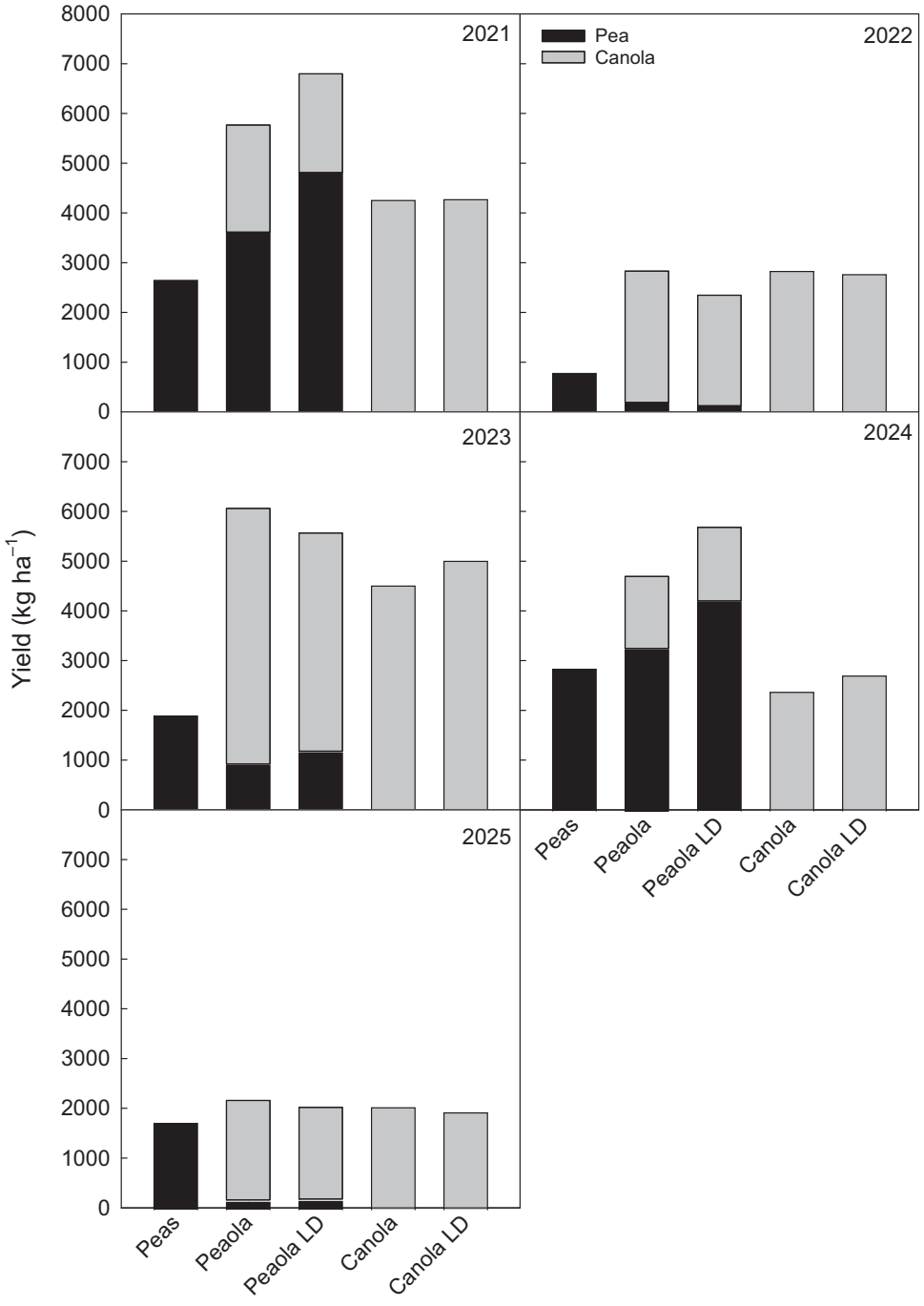


FIGURE 2 Yield of sole and intercropped winter pea and canola cropping systems (2021–2025).

concentrations occurred in 2024 and 2025 ($p < 0.0001$; $p = 0.0003$), with sole-crop peas showing the highest levels, over 17 mg kg^{-1} (Table 4). In contrast, sole-crop canola systems had lower nitrate levels, ranging from 5.3 to 9.6 mg kg^{-1} across years. Intercropping peas with canola reduced residual soil nitrate compared to sole peas: both Peaola and Peaola LD systems showed intermediate nitrate concentrations, typically between 6.7 and 11.1 mg kg^{-1}. Ammonium concentrations were more variable across systems and years, with no clear pattern or significant cropping system effect ($p > 0.1$).

4 | DISCUSSION

Intercropping is widely recognized for its potential to improve land use efficiency, often quantified using LER. In spring annual intercrops, typical LER values range from 1.1 to 1.5, indicating that intercropping can produce 10%–50% more yield per unit area than monocultures (Mead & Willey, 1980; Yu et al., 2015). While most intercropping studies focus on spring-planted systems, emerging research on winter intercropping, such as winter wheat and pea combinations, has

TABLE 4 Post-harvest soil nitrate (NO_3^--N) and ammonium (NH_4^+-N) concentrations in the 0- to 15-cm soil depth by crop and year, with associated *t*-values for cropping system (CS) effect.

	2022		2023		2024		2025	
	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})
Peas	17.3	2.2	7.6	1.5	17.6a	3.3	20.6a	1.4
Peaola	10.8	2.9	7.7	1.7	8.2b	2.7	9.3b	1.6
Peaola LD	11.1	2.6	6.7	1.6	8.2b	3.3	9.3b	1.7
Canola	9.6	2.0	6.4	1.5	5.3b	3.7	7.6b	1.5
Canola LD	13.2	1.9	6.8	1.6	5.9b	2.8	8.1b	1.8
Factor				*p*-value				
CS	0.074	0.129	0.884	0.855	<0.0001	0.586	0.001	0.294

Note: Within a given year and metric, means followed by different letters differ at $\alpha = 0.05$ (Tukey Honestly Significant Difference).

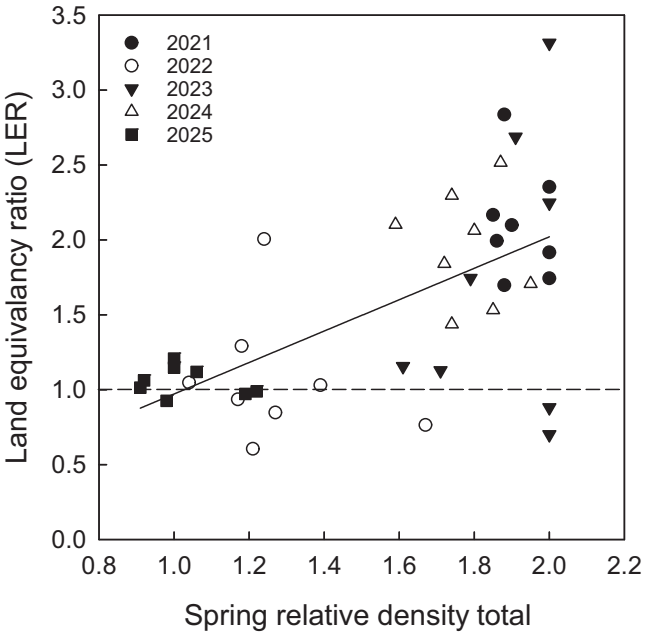


FIGURE 3 Land equivalent ratio (LER) as a function of total spring relative density. The solid line shows the fitted model (LER = 1.05 × Density − 0.0786; $R^2 = 0.6067$), with LER = 1 indicated by the dashed reference line.

demonstrated similar or even greater yield advantages under certain conditions (Vályi-Nagy et al., 2024). A key distinction between spring and winter intercropping lies in the challenge of overwinter survival. In winter systems, productivity and LER are highly dependent on the ability of both component crops to survive the cold season. Results from this study show that when winterkill of peas was extensive, LER values remained low, ranging from 1.0 to 1.3 in 2022 and 2025, and neither the NER_{Spring} (1.05–1.28) nor the TOI (0.55–1.1) indicated an advantage over the higher yielding sole-crop (Figure 4; Table 3; Table S7). Conversely, when pea survival was high, winter peaola produced LER values of 1.9 to 2.3 (2021 and 2024), supported by NER_{Spring} values of 1.84 to 2.17 and TOI values of 1.3 to 2.5, indicating true overyielding relative to the best-performing monoculture (Table 3; Figure 4). Notably, in high-survival years, pea yield within the intercrop exceeded that of the sole-crop, demonstrating that winter intercropping not only enhances efficiency but can also increase seed yield.

One of the key drivers of this enhanced productivity is the temporal partitioning of photosynthetically active radiation (PAR) between the component crops. Although temporal complementarity is often discussed in the context of relay systems or staggered planting, numerous studies show that strong complementarity can also emerge when crops are sown at the same time but diverge in phenological timing, canopy expansion, and peak resource demand (Dong et al., 2018). Work in simultaneous bean–maize intercrops demonstrates how

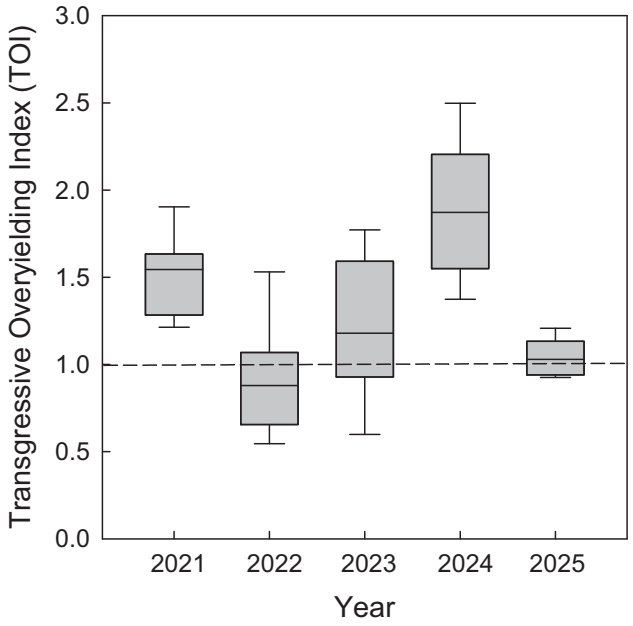


FIGURE 4 Year-to-year variation in the transgressive overyielding index (TOI) for the winter pea–canola intercrop. The dashed line indicates the break-even point where intercrop yield equals the highest yielding sole-crop.

natural differences in crop phenology can create sequential periods of canopy dominance and reduce direct competition for resources (Clark & Francis, 1985). These patterns are consistent with radiation-capture frameworks showing that complementary light interception often arises when intercrop species differ in their rates of leaf area development or occupy distinct vertical layers within the canopy (Keating & Carberry, 1993). In our winter intercropping system, the strong LER gains observed in high pea survival years reflect the same underlying principle: when both crops survived winter, their contrasting spring growth patterns created opportunities for complementary resource use that could not occur when one component crop is largely absent, a pattern strengthened in our low-N context where legume relative density has an outsized influence on intercrop performance (Yu et al., 2015).

Although winter pea and canola were sown concurrently, the two species diverged sharply in their spring growth trajectories due to differences in overwinter recovery, canopy architecture, and timing of senescence. Sole-crop canola consistently reached peak canopy light interceptance earlier in the season than sole-crop peas, reflecting a staggered spring growth pattern among crops. In contrast, peak interceptance in the intercropped systems occurred later, aligning more closely with the timing of sole-crop pea peak interceptance and coinciding with the decline in canola interceptance as the crop began to senesce. This temporal complementarity mirrors patterns documented by Dong et al. (2018) who showed that the suppressed species delays its maximum growth rate until the dominant canopy begins to decline.

In addition to these temporal dynamics, there were also structural advantages within the intercrop. In sole-crop systems, peas typically form a compact canopy with a median pod height of 49 cm. While the canopy does knit together to provide some self-support, it often lodges during the seed-filling stage, reducing airflow and creating a microclimate conducive to disease development (Wang et al., 2006). In contrast, intercropped peas benefit from the structural support of canola, whose pods reach a median height of 115–116 cm, providing an effective scaffold upon which the pea canopy can stretch vertically. In years with high LER, visual observations confirmed that pea foliage not only filled the inter-row spaces between canola rows but also extended above the canola canopy, capturing light that would otherwise be lost in a sole-crop canola system (Figure 1; Figure 7). This scaffolding effect, where peas climb and use taller companion crops for mechanical support, reduces lodging and allows the legume canopy to occupy higher canopy positions, a pattern also observed in other cereal–legume intercrops (Podgórska-Lesiak & Sobkowicz, 2013).

This vertical repositioning of the pea canopy also carries important consequences for reproductive physiology and productivity. Positioning pea pods and stems in brighter canopy zones enhances their photosynthetic contribution and improves harvestability, particularly as these organs can supply a substantial fraction of total canopy carbon gain (Lawson & Milliken, 2023; Simkin et al., 2020). These shifts align with the broader intercropping literature showing that canopy architecture strongly influences performance. For example, the importance of vertical canopy structure in determining competition outcomes has been demonstrated in barley–pea mixtures (Berntsen et al., 2004), and mechanical support for climbing pea has been observed in cereal and oilseed-based intercrops (Blanc et al., 2024; Madsen et al., 2022; Podgórska-Lesiak & Sobkowicz, 2013). Together, these temporal and structural mechanisms help to explain the enhanced PAR capture, increased pea yield, and higher LER, NER, and TOI values observed in favorable years.

Finally, post-harvest soil nitrate patterns provide tentative evidence for improved nitrogen use efficiency in the intercrop, as nitrate concentrations were consistently lower in intercropped and sole-canola systems than in sole peas. While this is consistent with previous legume–non-legume intercropping studies (Blackshaw et al., 2010; Szumigalski & Van Acker, 2006), this interpretation is based solely on measurements from the 0 to 15 cm soil layer and does not capture deeper nitrate pools or confirm biological nitrogen fixation. Without complementary data such as tissue nitrogen concentration, percent nitrogen derived from fixation, or isotopic analysis (e.g., δ^{15}N [ratio of ^{15}N to ^{14}N isotopes]), the extent of nitrogen sparing and potential transfer between species

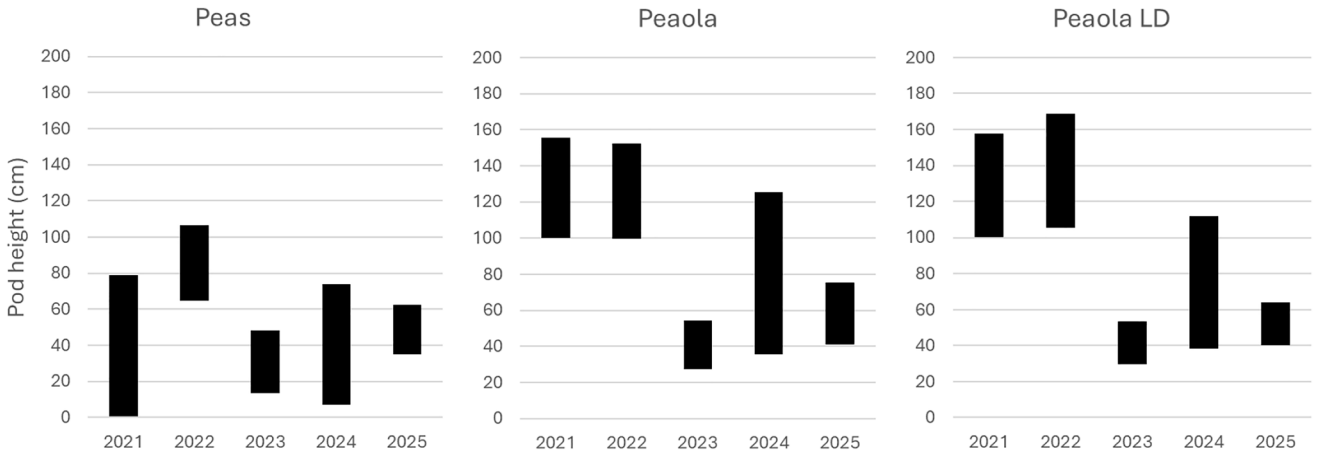


FIGURE 5 Pea pod height distribution at maturity in pea and canola cropping systems across the 5 years of study (2021–2025).

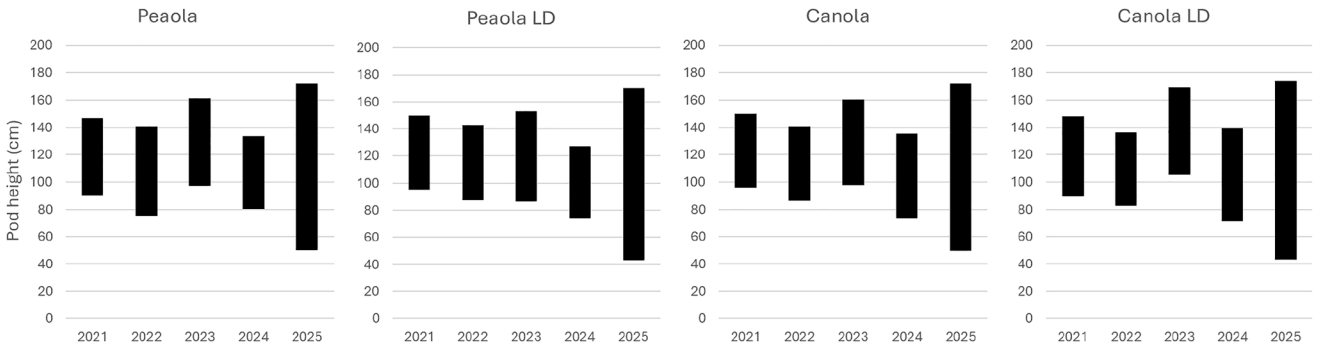


FIGURE 6 Canola pod height distribution at maturity in pea and canola cropping systems across the 5 years of study (2021–2025).



FIGURE 7 Winter peas overtopping winter canola when intercropped (winter peaola). Photo taken on June 10, 2021.

cannot be conclusively determined. Consequently, while the observed differences suggest reduced nitrate accumulation in intercrops, they should be interpreted cautiously, as they may reflect redistribution rather than true sparing. Future research should incorporate isotopic techniques and whole-profile soil sampling to directly quantify nitrogen dynamics, validate fixation contributions, and assess whether intercropping confers measurable benefits in nitrogen cycling beyond surface soil layers.

5 | CONCLUSION

This 5-year study demonstrates that winter intercropping of pea and canola can significantly enhance land use efficiency and pea productivity under temperate conditions, provided that overwinter survival is maintained. The highest LERs, approaching or exceeding 2.0, were observed in years with strong pea survival, confirming that winter intercropping can outperform sole-cropping systems in terms of yield per unit area. These outcomes were corroborated by the NER_{Spring}, which exceeded 1.0 in the same high-survival years, indicating that intercrop productivity surpassed expectations based on sole-crop yields. Transgressive overyielding (TOI > 1) in 2021 and 2024 further demonstrated that the intercrop outperformed the best-yielding component crop in favorable years. Key mechanisms underpinning this enhanced performance include staggered canopy light interceptance and the vertical scaffolding of the pea canopy. Pea foliage extending above the canola canopy captured light otherwise lost during senescence, while elevated pod placement improved harvestability and potentially increased photosynthetic contribution from reproductive tissues. These dynamics illustrate how intercropping can optimize both source and sink functions within the canopy.

Management practices such as reduced canola density and low spring nitrogen inputs supported intercrop complementarity, and although canola yields declined in high-LER and high-NER_{Spring} years due to competition from vigorous peas, overall system productivity improved. These yield dynamics also contributed to the system's year-to-year performance. While intercropping is often associated with greater stability through compensatory interactions (e.g., Raseduzzaman & Jensen, 2017), stability in this winter system was driven far more by pea overwinter survival than by buffering between species. In years with strong pea survival, pea yields were stable and the intercrop performed well despite increased variability in canola yield. However, years with substantial pea winterkill showed reduced system-level stability, with the intercrop functioning more like a sole-crop canola stand. Thus, winter peaola did not inherently increase yield stability relative to sole-crops, and its performance remained tightly constrained by the reliability of winter pea survival.

This observation points toward the possibility for adaptive in-season nutrient management. When poor pea survival is observed in early spring, producers could pivot to managing the stand as a sole-crop canola system by applying spring nitrogen at rates consistent with standard sole-crop recommendations. While this approach was not tested here, it highlights a promising avenue for enhancing system-level resilience in regions where winterkill is frequent. Future research should therefore evaluate whether flexible fertilizer adjustments or conditional management approaches can buffer yield stability while maintaining the productivity advantages observed in high-survival years.

AUTHOR CONTRIBUTIONS

Eric R. Page: Conceptualization; formal analysis; funding acquisition; methodology; project administration; supervision; validation; visualization; writing—original draft; writing—review and editing. **Jamie Larsen**: Conceptualization; methodology; writing—review and editing. **Sydney Meloche**: Investigation. **Alyssa Thibodeau**: Investigation. **Emma Bedal**: Investigation. **Meghan Moran**: Writing—review and editing. **Brian Caldbeck**: Writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

ORCID

Eric R. Page https://orcid.org/0000-0003-3361-5151

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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