

## ORIGINAL ARTICLE

Special Section: Intercropping for Sustainable Agriculture: Successes, Challenges, and Opportunities

# Optimizing seeding ratios of field pea–brown mustard intercrops in Atlantic Canada

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## Abstract

Intercropping is a promising approach for ecological intensification that can enhance productivity and agroecosystem services. This study evaluated the agroecological performance of field pea (*Pisum sativum*) and brown mustard (*Brassica juncea*) intercropping across seeding ratios (0.5×, 1.0×, and 1.5× the recommended rates; 100 seeds m<sup>-2</sup> recommended seeding rate for each crop) at 4-site years in Atlantic Canada: Canning, NS (2020); Harrington, PEI (2021); New Glasgow, PEI (2022); and Truro, NS (2024). Treatments were arranged in a randomized completed block design at each site-year. Measurement for seed yield, land equivalent ratio (LER), and weed suppression were taken. Recommended or higher seeding rates (1.0× and 1.5×) achieved greater yields and higher LER (1.48–1.78) than sole crops (LER of 1), while the lowest seeding rate (0.5×) reduced pea yield by 38% and reduced mustard yield by 33%. Across site-years, pea yield averaged 2507 kg ha<sup>-1</sup> at 1.0× (100 seeds m<sup>-2</sup>) or 1.5× (150 seeds m<sup>-2</sup>) compared to 1547 kg ha<sup>-1</sup> at 0.5× ( $p < 0.001$ ). Brown mustard showed a similar trend, yielding an average of 476 kg ha<sup>-1</sup> at 1.0× (100 seeds m<sup>-2</sup>) or 1.5× (150 seeds m<sup>-2</sup>) versus 320 kg ha<sup>-1</sup> at 0.5× (50 seeds m<sup>-2</sup>). Weed biomass declined significantly under intercropping, with the greatest suppression (62%) observed at the 1.5×:1.5× ratio at Truro (2024). Although combined site-year data provide general trends, significant site-year × treatment interactions suggest environmental and management factors influenced outcomes. Overall, pea–mustard intercropping at recommended or higher seeding rates improves land-use efficiency and weed control, supporting its potential as a component in diversified and sustainable cropping systems.

**Abbreviations:** BNF, biological nitrogen fixation; LER, land equivalent ratio; WSE, weed smother efficiency.

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### Plain Language Summary

Researchers in Atlantic Canada tested intercropping field peas with brown mustard at three seeding rates: half, standard, and one-and-a-half times the usual amount. Standard or higher rates performed best, producing greater yields for both crops and improving land-use efficiency by 48%–78% (land equivalent ratio 1.48–1.78) compared to growing each crop alone. Higher rates also reduced weed biomass by up to 62%, likely due to mustard natural weed-suppressing chemicals and better canopy coverage. While weather and pests caused some variation, pea-mustard intercropping at recommended or higher densities proved to be an effective, low-input strategy for boosting productivity and controlling weeds sustainably.

## 1 | INTRODUCTION

Industrialized agricultural systems, dominated by monocultures, have achieved high yields through chemical inputs and mechanization. However, these systems increasingly face challenges like inefficiency, pest pressure, and soil degradation (Bourke et al., 2021), highlighting the need for diversified cropping strategies. Intercropping, the practice of growing two or more crops in the same field during all or part of a growing season (such as legume-brassica intercropping), has emerged as a promising pathway toward sustainability (Brooker et al., 2015). By improving resource use efficiency and reducing reliance on external inputs (Brooker et al., 2015), intercropping can enhance land use efficiency, often quantified by land equivalent ratio (LER). LER is a measure of the land area required under sole cropping to match intercrop yields (Willey, 1979). Empirical evidence supports these land-use efficiency benefits. Maize-pea intercropping has produced LER values ranging from 1.18 to 1.47 (Mao et al., 2012); barley-pea intercrops in British Columbia reported LERs greater than 1.0 (Chapagain & Riseman, 2014); and chickpea-flax intercrops in southern Saskatchewan produced higher total yields and nutrient uptake efficiencies compared to sole crops, also exhibiting favorable LER values (Reid et al., 2023). Notably, pea-wheat intercropping enhances nitrogen use efficiency (NUE) under low-N conditions, with an average LER of 1.15 across various N treatments, demonstrating its superiority over monocropping (Bedoussac & Justes, 2011). These advantages arise from complementary resource use, as different species exploit soil nutrients and water more effectively, enabling mixed cultures to outperform monocultures (Brooker et al., 2015; Gebru, 2015; Akchaya et al., 2025).

Weeds remain a major constraint on crop productivity via competition for light, water, and nutrients, often causing substantial yield penalties (Singh et al., 2022; Pavlović et al., 2022). Intercropping can suppress weed growth, thereby reducing herbicide requirements. Certain Brassica species,

such as brown mustard (*Brassica juncea*), possess allelopathic properties, primarily due to glucosinolates, that inhibit weed germination and growth in certain weed species (Weston & Mathesius, 2013). Glucosinolate content and biofumigation potential vary significantly among Brassica species, influencing their capacity to suppress weeds and pathogens (Batistič et al., 2025). In contrast, field pea (*Pisum sativum*), particularly in semi-leafless cultivars, is a relatively weak early-season competitor (Spies et al., 2011). In monoculture systems, this vulnerability often translates to substantial yield losses under weed pressure (Bailey-Elkin et al., 2022). Pairing pea with allelopathic mustard could therefore provide complementary weed suppression (Björkman et al., 2015; Weston & Mathesius, 2013).

Beyond weed management, legume-brassica intercropping has important implications for nutrient cycling. Legumes fix atmospheric nitrogen (N) via biological nitrogen fixation (BNF), reducing reliance on synthetic fertilizers and enhancing soil fertility and crop productivity (Meißner, 2021; Yu et al., 2015). In intercropping systems, BNF by the legume component is often stimulated by the non-legume partner as it depletes mineral N (Peoples et al., 2009). This fixed N can partially meet the N demand of the intercropped brassica and improve NUE at the system level (C. Li et al., 2020). However, the specific N dynamics and competitive interactions in pea-mustard intercropping remain poorly quantified, particularly regarding the balance between stimulated BNF and interspecific competition for early-season mineral N (Corre-Hellou et al., 2006). These benefits underline the critical role of legumes in sustainable agriculture, especially within intercropping systems.

Planting ratios in intercrop systems influence agroecological impacts and crop yield and quality parameters. For instance, a maize-bean system with a 1:2 row ratio effectively reduced weed biomass (Workayehu & Wortmann, 2011). However, limited research exists on pea-mustard intercropping, particularly regarding how different planting ratios influence weed suppression, seed yield, and land use

efficiency in Atlantic Canada. Given the synergy between mustard's allelopathic weed suppression and pea's N fixation, systematic evaluation across density gradients is warranted for temperate agroecosystems. Developing a new intercropping system in Atlantic Canada, incorporating high-value crops like field pea and brown mustard, enhances the sustainability of regional agricultural rotations, supporting minor and emerging commodities and value-added products, and expanding opportunities in export markets and trade. We hypothesized that intercropping field pea with brown mustard at recommended or higher seeding rates would increase system productivity, land-use efficiency ( $LER > 1$ ), and weed suppression relative to sole cropping, whereas low seeding rates would reduce these benefits due to insufficient crop density. Accordingly, this study evaluated the performance of various pea-mustard seeding ratios in pea-mustard intercrops by assessing (1) seed yield of each species, (2) land-use efficiency using the LER, and (3) weed biomass and suppression efficiency.

## 2 | MATERIALS AND METHODS

### 2.1 | Experimental design and crop management

This study evaluated pea and brown mustard intercropping at various seeding ratios (50, 100, and 150 seeds  $m^{-2}$  for each species, corresponding to 0.5 $\times$ , 1 $\times$ , and 1.5 $\times$  the regionally recommended seeding rates for sole crop production in Atlantic Canada [Mills & Fillmore, 2024]), alongside sole crop controls. This study offers several novel contributions compared to previous research: (1) It is among the first systematic investigations of a full gradient of sowing ratios (ranging from 0.5 $\times$  to 1.5 $\times$  for both species) in pea-mustard intercropping, moving beyond simple sole-crop versus intercrop comparisons; (2) Our integrated assessment of agronomic (seed yield), ecological (LER), and weed suppression metrics provides a more holistic evaluation of system performance; and (3) Multi-environment trials across Atlantic Canada supply much-needed regional data for this understudied cropping system. The "recommended" or 1.0 $\times$  seeding rate for both pea and mustard was based on regional agronomic guidelines for sole-crop production in the region. The 0.5 $\times$  and 1.5 $\times$  rates represent deviations from this standard to create a density gradient for examining competition and complementarity.

Field experiments were conducted across 4-site years in Nova Scotia and Prince Edward Island; weather details are provided in Table 1. Field trials used pea (cv. CDC Saffron) and brown mustard (cv. Centennial), selected for their similar days to maturity. Plots measured 1.25 m  $\times$  6 m and were seeded using a small-plot seed drill (Wintersteiger). From

### Core Ideas

- Pea-mustard intercropping at  $\geq$  recommended seeding rates (100 and 150 seeds  $m^{-2}$ ) boosts total yield and LER (1.48–1.78), enhancing land-use efficiency in Atlantic Canada.
- Higher seeding rates (1.0 $\times$  and 1.5 $\times$ ) in pea-mustard intercrops yielded 38% more pea and 33% more mustard than the low rate (0.5 $\times$ ), with strong site variability.
- Pea-brown mustard intercropping suppresses weeds up to 62% at 1.5 $\times$ :1.5 $\times$  ratio, leveraging mustard allelopathy for sustainable weed control.

2020 to 2022, 11 treatments were implemented, comprising three seeding rates for each crop (0.5 $\times$ , 1.0 $\times$ , and 1.5 $\times$  recommended rates), yielding nine intercropping combinations and two sole crop treatments (pea only and mustard only) (Table 2). These sole crop treatments served as agronomic controls for yield and LER comparisons. In 2024, an additional empty plot was included to assess background weed pressure, increasing the total to 12 treatments. For each site-year, experimental units were arranged in a randomized complete block design with three blocks at Canning, NS 2020, and four blocks at the other three sites. Pea was seeded first using a seed drill at a depth of 2–3 cm with eight rows spaced 15 cm apart, and the plot length was 6 m. Brown mustard was then seeded using the same seed drill at a depth of 0.6 cm, mixed within the same rows (additive design; an example shown in Figure 1). Figure 1 shows pea-brown mustard intercropping, with seeding rates of 150 seeds  $m^{-2}$  for pea and 50 seeds  $m^{-2}$  for brown mustard.

### 2.2 | Field management

A pre-emergent herbicide (trifluralin 480 g  $L^{-1}$  a.i.) was applied and incorporated into the soil using tillage in two perpendicular directions prior to seeding at Canning 2020, Harrington 2021, and New Glasgow 2022 to control annual grasses and broadleaf weeds, in accordance with the herbicide label. Throughout the season of 2020, plots were hand weeded 4 times to minimize weed pressure. In contrast, at Truro in 2024, only a pre-plant burndown herbicide (glyphosate at 540 g  $L^{-1}$  a.i.) was applied, followed by a single manual weeding conducted approximately 15 days after emergence; no manual weeding occurred after this, which allowed for determination of treatment effects on weed suppression. Fertilizer regimes were consistent across both years: Urea (46-0-0) was used as the N source and was applied broadcast by hand within 1 week of seeding. Rates differed: 60 kg N  $ha^{-1}$  for

**TABLE 1** Monthly mean temperature (°C) and monthly total precipitation (mm) for the four experimental site-years in Atlantic Canada.

Site-year	Monthly mean temperature (°C)					Monthly total precipitation (mm)				
	May	June	July	August	September	May	June	July	August	September
Canning, NS 2020	10.5	17.3	20.2	20.2	15.3	78	49.1	114.9	70.6	121.8
Harrington, PEI 2021	8.5	17.4	17.6	20.5	16.1	107.3	66.8	134.1	31.8	226.8
New Glasgow, PEI, 2022	9.5	15.2	20.2	20.2	14.8	33.9	131.6	114.2	73.2	155.1
Truro, NS, 2024	11.4	16.2	19.9	18.7	14.3	46.7	124.0	81.9	109.6	67.6

Abbreviations: NS, Nova Scotia; PEI, Prince Edward Island.

**TABLE 2** List of experimental treatments.

Treatment	Pea density (seeds/m <sup>2</sup> )	Mustard density (seeds/m <sup>2</sup> )	Description
P1.0:M0.0	100	0	Pea only
P0.0 M:1.0	0	100	Mustard only
P0.5:M0.5	50	50	Pea 50: Mustard 50
P0.5:M1.0	50	100	Pea 50: Mustard 100
P0.5:M1.5	50	150	Pea 50: Mustard 150
P1.0:M0.5	100	50	Pea 100: Mustard 50
P1.0:M1.0	100	100	Pea 100: Mustard 100
P1.0:M1.5	100	150	Pea 100: Mustard 150
P1.5:M0.5	150	50	Pea 150: Mustard 50
P1.5:M1.0	150	100	Pea 150: Mustard 100
P1.5:M1.5	150	150	Pea 150: Mustard 150
Empty plot <sup>a</sup>	0	0	Weedy plot

<sup>a</sup>The empty plot treatment was included only at the Truro 2024 site.

intercrops, 20 kg N ha<sup>-1</sup> for sole pea, and 100 kg N ha<sup>-1</sup> for sole mustard, to optimize each system. The different N levels were an intentional design choice to reflect real-world, optimized management for each cropping system. Applying 100 kg N ha<sup>-1</sup> to sole pea would be agronomically inefficient and environmentally unsound, while under-fertilizing sole mustard would not represent its yield potential. Our design compares agronomically optimized sole cropping systems against an intercropping system managed with a single, intermediate N rate. This tests the system's performance under a practical management scenario. Decisions regarding phosphorus (P) and potassium (K) application were based on pre-plant soil tests (Table 3). Since P and K levels were adequate according to the soil test, no additional P or K was applied.

## 2.3 | Data collection

Stand counts were conducted approximately 3 weeks after seeding. A 0.5 m × 0.5 m quadrat was placed randomly twice within the inner area of each plot, avoiding border rows. The number of plants of each species within the quadrat

was counted and converted to plants per square meter. Stand count data showed that plant densities were lower than the seeding rates, as expected; however, the relative proportions among treatments were consistent with the seeding rates and therefore are not presented in the results. At maturity, plots were harvested using a plot combine harvester. The two crop species matured nearly synchronously, allowing for a single combined harvest. Seed separation and cleaning were conducted using a mechanical cleaner (Clipper Seed Cleaning Co.). The harvested mixture was first passed through the cleaner, which utilized screens and air flow to separate seeds based on size and density. Following mechanical separation, a minor amount of hand-sorting was performed to ensure >99% purity. The final seed yield was adjusted to a standard moisture content of 13% for pea and 8% for brown mustard.

## 2.4 | Land equivalent ratio

The efficiency of pea and mustard intercropping systems was evaluated using LER (Willey, 1979). The calculation was based on the yield of intercropped species compared to the yield of the same species grown in monocrop. LER for a pea–

TABLE 3 Soil chemical properties at four field sites in Atlantic Canada prior to planting.

Site	Year	Organic matter (%)	pH	CEC (meq 100 g <sup>-1</sup> N)	Total N (%)	P <sub>2</sub> O <sub>5</sub> (kg ha <sup>-1</sup> )	K <sub>2</sub> O (kg ha <sup>-1</sup> )	Ca (kg ha <sup>-1</sup> )	Mg (kg ha <sup>-1</sup> )	Na (kg ha <sup>-1</sup> )	S (kg ha <sup>-1</sup> )	B (mg ha <sup>-1</sup> )	Cu (mg ha <sup>-1</sup> )	Zn (mg ha <sup>-1</sup> )	Mn (mg ha <sup>-1</sup> )	Fe (mg ha <sup>-1</sup> )
Canning, NS	2020	2.8	5.62	9.1	-	982	299	2155	210	35	25	<0.5	9.12	3.72	17	370
Harrington, PEI	2021	2.9	6.6	9	-	332	124	642	81	18	19	0.5	1.3	2.1	32	265
New Glasgow, PEI	2022	2.9	6.4	10	-	568	404	2030	186	20	34	0.4	0.8	1.2	38	177
Truro, NS	2024	3.3	6	10.3	0.17	1288	167	3072	190	10	19	≤0.5	1.1	3.1	58	174

Note: Values represent composite soil samples from the 0- to 15-cm depth. Abbreviations: NS, Nova Scotia; PEI, Prince Edward Island.



FIGURE 1 Plot image showing the additive design of pea–brown mustard intercrops with seeding rates of 150 seeds m<sup>-2</sup> for pea and 50 seeds m<sup>-2</sup> for brown mustard, taken on June 24, 2020, at Canning, NS.

mustard intercrop was the sum of the partial LER values for pea ( $LP$ ) and mustard ( $LM$ ):

$$LP = \frac{Y_{\text{pea IC}}}{Y_{\text{pea SC}}}$$

$$LM = \frac{Y_{\text{mustard IC}}}{Y_{\text{mustard SC}}}$$

$$LER = LP + LM$$

where  $Y_{\text{pea}}$  and  $Y_{\text{mustard}}$  were the seed yields of pea and brown mustard, respectively, and IC and SC stand for intercrop and sole crop. An LER value > 1 indicates intercropping is more efficient in land use compared to sole cropping, whereas an LER < 1 suggests that intercropping requires more land to achieve yields equivalent to those of sole crops.

## 2.5 | Weed survey and analysis at Truro, NS, in 2024

Weed density counts and identification to the species level using standard field guides were conducted 10 days after the onset of flowering in mustard flowering, coinciding with the beginning of pea flowering. Weed density was recorded by species using a 0.5 m × 0.5 m quadrat placed at two random locations within each plot, avoiding border rows. At full maturity, pea, mustard, and combined weeds were hand-harvested from within two separate, non-overlapping 0.5 m × 0.5 m quadrats per plot. The harvested material was dried in an oven for >48 h, and complete dryness was ensured by confirming that no weight change occurred after two additional hours in the oven. Pea, mustard, and total weed biomass were weighed and recorded following the first harvest.

Weed smother efficiency (WSE) was calculated to assess the effectiveness of intercropping systems in reducing weed biomass. WSE is expressed as the percentage reduction in weed biomass in intercropping compared to sole cropping systems, calculated using the following equation (Geetha et al., 2019):

$$\text{WSE} = \frac{W_{\text{sc}} - W_{\text{ic}}}{W_{\text{sc}}} \times 100\%$$

where  $W_{\text{sc}}$  is the weed biomass in the sole crop system and  $W_{\text{ic}}$  is the weed biomass in the intercropping system. Higher WSE values indicate greater weed suppression.

## 2.6 | Statistical analysis

Statistical analyses were conducted using Minitab software (version 22.1; Minitab LLC.). A mixed-model analysis of variance (ANOVA) was performed with treatment as the fixed effect and site-year, blocks nested within site-year, and site-year × treatment interactions as random effects. Variance components were estimated using restricted maximum likelihood, and degrees of freedom for fixed effects were determined using the Kenward-Roger method. Due to significant site-year × treatment interactions for pea seed yield (Table S1) and LER (Table S2), data from each site-year were analyzed separately. All measured variables were verified to meet ANOVA assumptions, including normality of residuals, homogeneity of variance, and independence of observations. Outliers were identified using standardized residuals exceeding ± 3. Fisher's least significant difference test, with a significance level of  $\alpha = 0.05$ , was used to compare treatment differences when significant effects were detected.

## 3 | RESULTS

### 3.1 | Pea-mustard intercropping on pea seed yield

Treatments involving different seeding ratios of pea-mustard intercrops and two sole crop controls had significant effects on pea seed yield across combined site-years and within each site-year (Table 4; Figure 2). Across combined site-years, pea seed yield was higher at the recommended seeding rate (100 seeds  $\text{m}^{-2}$ ) and at 1.5× recommended seeding rate (150 seeds  $\text{m}^{-2}$ ) compared to the yield at 0.5× the recommended rate (50 seeds  $\text{m}^{-2}$ ; 1548 kg  $\text{ha}^{-1}$  pea yield) ( $p < 0.001$ ; Table 4; Figure 2a). The average pea seed yield at the 1× and 1.5× rates was 2507 kg  $\text{ha}^{-1}$ .

At Canning, NS, 2020, the sole pea treatment (3828 kg  $\text{ha}^{-1}$ ;  $p < 0.001$ ) yielded significantly higher than all intercropping treatments. Among intercrops, P1.5:M0.5 (2888 kg  $\text{ha}^{-1}$  pea yield) outperformed most others, while P0.5:M1.5 had the lowest pea yield (632 kg  $\text{ha}^{-1}$  pea yield) (Figure 2b). At Harrington, PEI, 2021, the highest yields occurred in P1.5:M1.0 (3780 kg  $\text{ha}^{-1}$  pea yield), P1.5:M1.5 (3750 kg  $\text{ha}^{-1}$  pea yield), and P1.0:M0.5 (3438 kg  $\text{ha}^{-1}$  pea yield), all higher than the sole pea treatment (2732 kg  $\text{ha}^{-1}$  pea yield) and lower ratio intercrops ( $p < 0.0001$ , Figure 2c). At New Glasgow, PEI (2022), pea seeding rates at or above the recommended level (1.0× and 1.5×) resulted in higher yields compared to P0.5:M0.5 and P0.5:M1.5. Specifically, P0.5:M0.5 (2627 kg  $\text{ha}^{-1}$  pea yield) and P0.5:M1.5 (2634 kg  $\text{ha}^{-1}$  pea yield) yielded significantly less compared to the majority of other treatments ( $p < 0.0001$ , Figure 2d). At Truro in 2024, pea yields were generally lower than in other site-years; higher pea seeding rate (1.5×) increased yields (818–957 kg  $\text{ha}^{-1}$  pea yield) compared to sole pea (527 kg  $\text{ha}^{-1}$  pea yield) and lower-ratio intercropping treatments ( $p < 0.0001$ , Figure 2c).

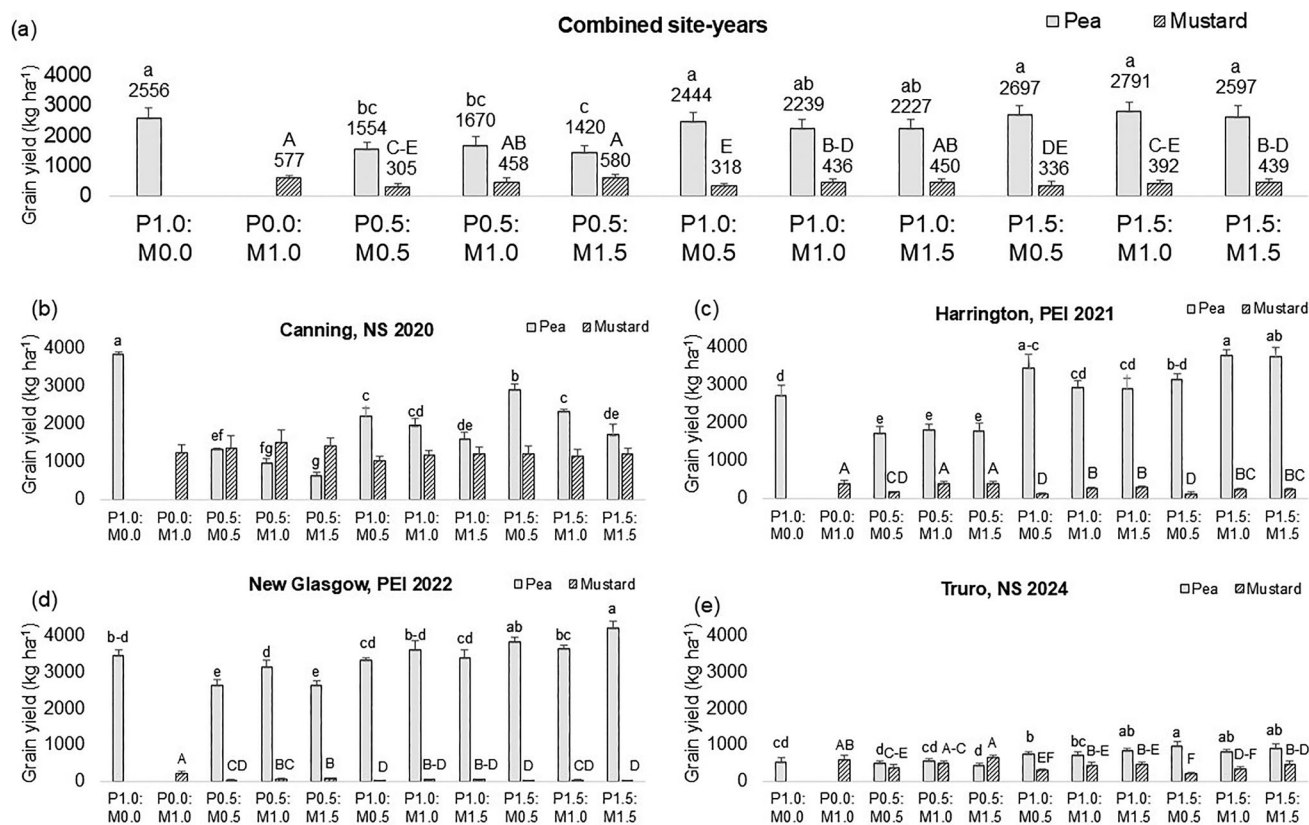
### 3.2 | Pea-mustard intercropping on mustard seed yield

A similar pattern was observed for brown mustard seed yield. Variations in pea-mustard seeding ratios and the two sole crop controls significantly affected mustard yield within each site-year and across combined site-years (Table 4; Figure 2a). When site-years were combined, mustard seed yield was highest at the recommended seeding rate (1.0×), whether grown as a sole crop or intercrop, and at the 1.5× rate ( $p < 0.001$ ; Table 4; Figure 2a). Mustard seed yield was less responsive to seeding ratio changes in intercropping combinations (Table 4). There were no significant differences in mus-

**TABLE 4** Results from mixed-model analysis of variance (ANOVA) tests of fixed effects for different pea-mustard intercropping seeding ratios, showing their impact on pea seed yield ( $\text{kg ha}^{-1}$  at 13% moisture), mustard seed yield ( $\text{kg ha}^{-1}$  at 8% moisture), and land equivalent ratio (LER) across site-years in Atlantic Canada (2020–2024).

Site-year	Response variables	DF Num	DF Den	F value	p value
Combined site-years	Pea seed yield	9.00	26.52	4.33	<0.0001
	Mustard seed yield	9.00	124.20	6.04	<0.0001
	LER	10.00	30.47	6.03	<0.0001
Canning, NS 2020	Pea seed yield	9.00	20.00	32.14	<0.0001
	Mustard seed yield	9.00	18.00	0.45	0.892
	LER	10.00	22.00	1.75	0.132
Harrington, PEI 2021	Pea seed yield	9.00	27.00	14.19	<0.0001
	Mustard seed yield	9.00	26.04	13.34	<0.0001
	LER	10.00	30.00	13.93	<0.0001
New Glasgow, PEI 2022	Pea seed yield	9.00	28.00	9.28	<0.0001
	Mustard seed yield	9.00	25.13	12.34	<0.0001
	LER	10.00	29.14	2.97	0.011
Truro, NS 2024	Pea seed yield	9.00	26.03	8.68	<0.0001
	Mustard seed yield	9.00	27.00	5.93	<0.0001
	LER	10.00	29.02	11.34	<0.0001

Note: DF Num refers to the numerator degrees of freedom and DF Den refers to the denominator degrees of freedom.



**FIGURE 2** Effects of pea–brown mustard seeding ratios on grain yields of pea ( $\text{kg ha}^{-1}$  at 13% moisture; solid gray bars) and brown mustard ( $\text{kg ha}^{-1}$  at 8% moisture; shaded dashed bars) for (a) combined site-years, (b) Canning, NS (2020), (c) Harrington, PEI (2021), (d) New Glasgow, PEI (2022), and (e) Truro, NS (2024). Within each panel, means sharing a common letter are not significantly different at  $p < 0.05$ ; lowercase letters indicate pea yield, and uppercase letters indicate mustard yield.

tard seed yield among treatments at Canning, NS, 2020. At Harrington, PEI, 2021, the sole mustard (480 kg ha<sup>-1</sup>), P0.5:M1.0 (409 kg ha<sup>-1</sup>), and P0.5:M1.5 (399 kg ha<sup>-1</sup>) treatments yielded significantly higher than the P1.0:M0.5 (120 kg ha<sup>-1</sup>), P1.5:M0.5 (129 kg ha<sup>-1</sup>), P1.0:M1.5 (291 kg ha<sup>-1</sup>), and P1.5:M1.5 (240 kg ha<sup>-1</sup>) treatments ( $p < 0.001$ ). At New Glasgow, PEI (2022), brown mustard seed yields were low across all treatments. The sole mustard treatment (245.5 kg ha<sup>-1</sup>) significantly outperformed all intercropping treatments ( $p < 0.001$ ), which had low mustard yields (10.7–69.6 kg ha<sup>-1</sup>). At Truro, NS (2024), higher mustard seeding rates (e.g., P 0.5:M 1.5, 637 kg ha<sup>-1</sup>) significantly higher than the P1.5:M0.5 (205 kg ha<sup>-1</sup>) and P1.0:M0.5 (292 kg ha<sup>-1</sup>) treatments ( $p < 0.001$ ). The sole mustard yield (582 kg ha<sup>-1</sup>) was not significantly different from the highest-yielding intercropping treatments.

### 3.3 | Pea-mustard intercropping on LER

Across the combined site-years, all intercropping treatments had LER values greater than 1 (ranging from 1.22 to 1.78; Figure 3a). Treatment effects on LER were significant: nearly all intercrop combinations produced significantly higher LERs than monocrops (LER = 1), with the exception of the P0.5:M0.5 treatment, whose LER did not differ significantly from monocrops (Figure 3a).

At Canning, NS (2020), no significant differences in LER were observed between monocrops and any intercropping treatment (Figure 3b). At Harrington, PEI (2021), a pattern similar to the combined analysis was observed. All intercropping treatments, except for P0.5:M0.5, had significantly higher LER values than monocrops, with LERs ranging from 1.47 to 2.00 (Figure 3c). Further, at this site-year, several intercropping treatments, particularly P1.5:M1.0 (2.00) and P1.5:M1.5 (1.97), had significantly higher LERs than the P0.5:M0.5 (1.06), P0.5:M1.5 (1.65), and P1.0:M0.5 (1.56) ( $p < 0.001$ , Figure 3c). At New Glasgow, PEI (2022), the P1.5:M1.5 treatment produced the highest LER (1.31), which was significantly greater than the LERs of P0.5:M0.5 (0.87), P0.5:M1.0 (1.05), P1.0:M0.5 (1.04), P1.0:M1.0 (1.10), and the monocrops (LER = 1) ( $p = 0.011$ , Table 4; Figure 3d). At Truro, NS (2024), all intercropping treatments had significantly higher LER values than monocrops ( $p < 0.001$ ). Notably, P1.5:M1.5 (LER of 2.50) and P1.0:M1.5 (2.37) had particularly high LERs, significantly exceeding those of several lower-ratio seeding treatments (Figure 3d).

### 3.4 | Pea-mustard intercropping on weed suppression I at Truro, NS, in 2024

The intercropping ratio significantly affected weed density during the flowering stage, weed biomass at harvest, and

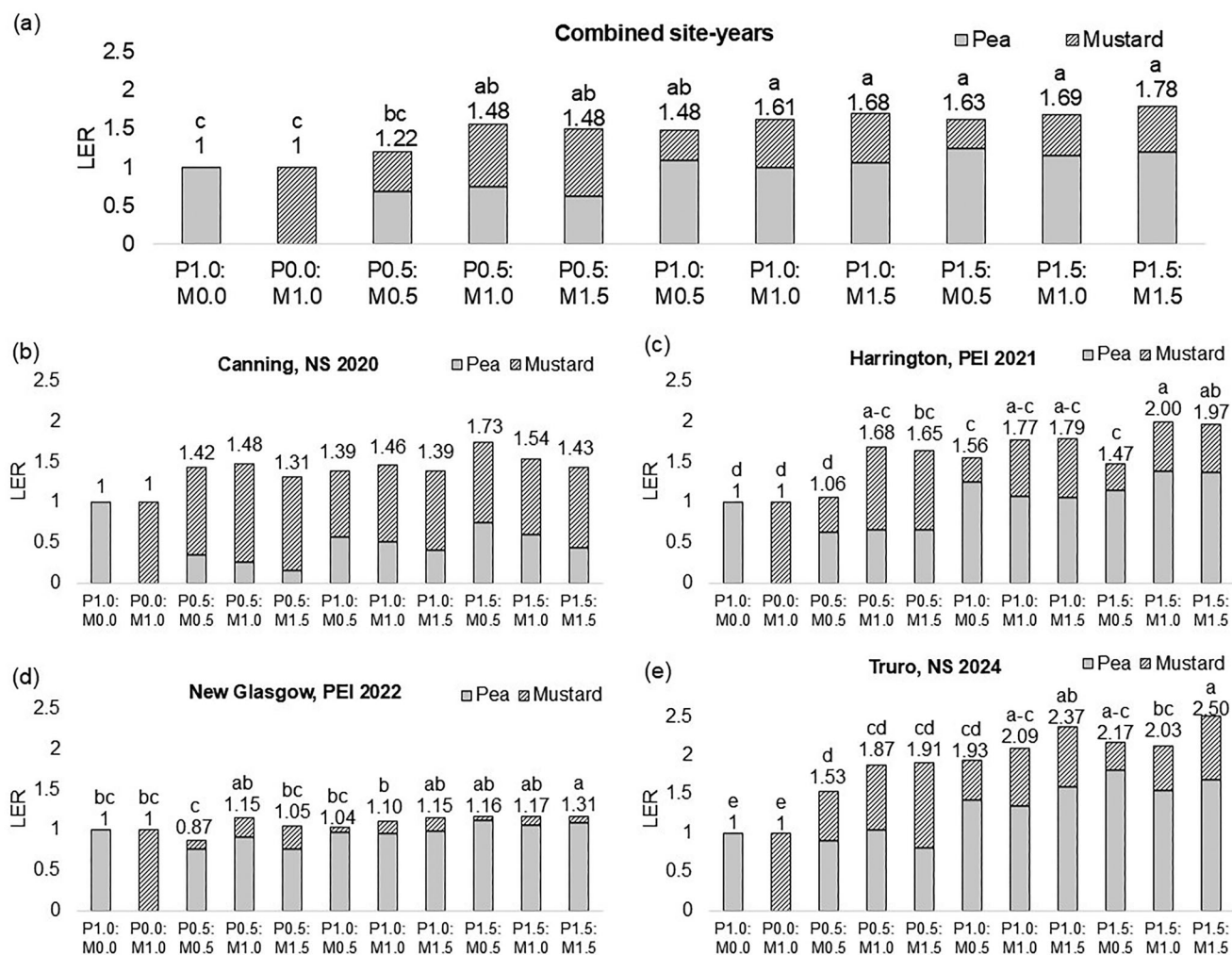
WSE at maturity in pea–brown mustard systems (Table 5). Weed density at flowering was highest in the fallow control (570 plants m<sup>-2</sup>) and did not differ significantly among sole-crop and intercropping treatments (247–314 plants m<sup>-2</sup>). Weed biomass at harvest followed a similar pattern, with the fallow control exhibiting the greatest values. Intercropping treatments with pea seeding rates of 1× and 1.5× the recommended level generally produced higher weed biomass than the respective sole crops. Nevertheless, these intercropping treatments provided superior weed suppression, with WSE values of 33.8%–61.7% compared to 19.0%–21.7% in sole crops.

Weed species identified in the field trial at Truro, NS (2024), are listed in Table 6. During the flowering stage (approximately 60 days after planting), the field was populated with various weed species, with over 50% species belonging to *Poaceae* family (*Digitaria ischaemum*, *D. sanguinalis*, *Panicum dichotomiflorum*, *P. capillare*, *Elymus repens*, *Setaria glauca*, *Setaria viridis*, and *Echinochloa crus-galii*). Other abundant weed species included *Chenopodium album* (*Amaranthaceae*), *Capsella bursa-pastoris* (*Brassicaceae*), and *Spergula arvensis* (*Caryophyllaceae*). At harvest, *D. ischaemum*, *D. sanguinalis*, and *C. album* dominated the weed population.

## 4 | DISCUSSION

### 4.1 | Grain yield response to seeding ratio in pea-mustard intercrop

The contrasting yield responses of pea and mustard across seeding ratios show the complexity of competitive and complementary interactions within this legume-brassica intercrop. A central finding is the strong positive response of pea yield to increased pea density, reflecting its capacity to dominate resource capture when present in large numbers. This pattern is consistent with broader intercropping theory, where increased density of a competitive species enhances its light interception and canopy occupancy (Raseduzzaman & Jensen, 2017). In our system, high pea density likely amplified the species' inherent advantages: rapid vertical extension, vining growth, and effective climbing on mustard stems, enabling efficient canopy penetration and light acquisition. Similar structural and resource-capture facilitation has been documented in cereal-legume intercropping meta-analyses that report increased stability and resource use efficiency under complementary canopy architectures (Lai et al., 2022). In addition, the dramatically low seed yield of brown mustard at the New Glasgow, PEI, 2022 site was due to severe flea beetle herbivory—a major constraint in Brassica production systems. Flea beetle outbreaks can concentrate feeding on reduced stands and substantially impair stand establishment (Soroka & Grenkow, 2013).



**FIGURE 3** Stacked bar charts showing the effects of pea–brown mustard seeding ratios on Land Equivalent Ratio (LER): pea LER (solid gray bars) and mustard LER (shaded dashed bars) for (a) combined site-years, (b) Canning, NS (2020), (c) Harrington, PEI (2021), (d) New Glasgow, PEI (2022), and (e) Truro, NS (2024). Within each panel, means sharing a common letter for total LER (sum of pea and mustard LER) are not significantly different at  $p < 0.05$ .

## 4.2 | Land-use efficiency and complementary interaction in pea–mustard intercrop

The consistently  $> 1.0$  LER across most site-years confirms that pea–mustard intercropping enhances land-use efficiency through complementary resource use. Such gains align with established ecological principles that resource partitioning—light, nitrogen, and spatial niches—drives overyielding in intercropping systems (Brooker et al., 2015). However, the exceptionally high LER values observed at Truro (up to 2.50) require careful interpretation. These values were partially inflated by severely reduced sole crop yields caused by intense weed competition, a factor known to artificially elevate LER when control plots suffer disproportionate stress (Saucke & Ackermann, 2006). Even so, intercrop plots at Truro retained greater productivity due to superior weed suppression, preserving system yield potential under adverse conditions.

Nitrogen-use complementarity remains a primary mechanism underpinning LER advantages. Pea relies predominantly on atmospheric  $N_2$  fixation, while mustard thoroughly exploits soil mineral N pools. Moderate N fertilization in our experiment likely maintained a balance where mustard competition sufficiently stimulated pea BNF without severely restricting overall crop growth. Such dynamics have been demonstrated in pea–canola systems, where canola-driven nitrogen depletion enhances pea  $N_2$  fixation and can stabilize yields under variable conditions (Madsen et al., 2022).

Site-specific outcomes further highlight the environmental dependence of intercrop benefits. At Canning (2020), optimal pea monoculture performance reduced the relative advantage of complementarity, whereas at New Glasgow (2022), mustard failure due to flea beetles disrupted interspecific interactions and eliminated the potential for overyielding. Studies in Brassica systems confirm that flea beetle outbreaks can fundamentally alter competitive dynamics by reducing

**TABLE 5** Effect of pea-mustard intercropping on weed density (plants  $m^{-2}$ ) at flowering, weed biomass at maturity, and weed smothering efficiency (WSE) at maturity at Truro, NS (2024).

Treatment	Weed density (plants per $m^{-2}$ )		Weed biomass (g $m^{-2}$ )		WSE (%)	
	With empty plot	Without empty plot	With empty plot	Without empty plot	With empty plot	Without empty plot
P1.0:M0.0	251 ± 57.6b	251 ± 57.6ab	492 ± 83.8ab	492 ± 83.8	19.0 ± 15.33de	19.0 ± 15.33c
P0.0:M1.0	242 ± 54.8b	242 ± 54.8ab	481 ± 84.0ab	481 ± 84.0	21.7 ± 13.12c–e	21.7 ± 13.12bc
P0.5:M0.5	249 ± 35.3b	249 ± 35.3ab	397 ± 78.2bc	397 ± 78.2	35.4 ± 13.28a–d	35.4 ± 13.28a–c
P0.5:M1.0	265 ± 26.8b	265 ± 26.8ab	350 ± 14.3bc	350 ± 14.3	42.5 ± 3.45a–d	42.5 ± 3.45a–c
P0.5:M1.5	314 ± 36.9b	314 ± 36.9a	401 ± 45.9bc	401 ± 45.9	34.8 ± 9.85a–d	34.8 ± 9.85a–c
P1.0:M0.5	276 ± 52.4b	276 ± 52.4ab	318 ± 22.5c	318 ± 22.5	47.5 ± 5.63a–c	47.5 ± 5.63ab
P1.0:M1.0	265 ± 58.7b	265 ± 58.7ab	306 ± 25.4c	306 ± 25.4	50.4 ± 2.51ab	50.4 ± 2.51a
P1.0:M1.5	285 ± 42.6b	285 ± 42.6ab	350 ± 41.9bc	350 ± 41.9	41.7 ± 9.18a–d	41.7 ± 9.18a–c
P1.5:M0.5	240 ± 41.4b	240 ± 41.4ab	257 ± 13.2c	257 ± 13.2	58.0 ± 2.19ab	58.0 ± 2.19a
P1.5:M1.0	236 ± 32.0b	236 ± 32.0b	255 ± 64.9c	255 ± 64.9	58.0 ± 11.27ab	58.0 ± 11.27a
P1.5:M1.5	247 ± 41.8b	247 ± 41.8ab	245 ± 71.4c	245 ± 71.4	61.7 ± 9.90a	61.7 ± 9.90a
Empty	570 ± 64.3a	–	616 ± 43.0a	–	0 ± 0e	–
<i>F</i> value	6.07	2.33	4.17	0.76	3.94	2.18
<i>p</i> value	<0.0001	0.033	0.001	0.664	0.001	0.049

Note: Data are presented as means across four replications with the standard error of the mean (SEM). Means sharing a common letter within each column are not significantly different at  $p < 0.05$ .

**TABLE 6** Weeds identified in the field trial at Truro, NS in 2024.

Plant family	Plant species
Amaranthaceae	<i>Chenopodium album</i>
Asteraceae	<i>Gnaphalium uliginosum</i> <i>Senecio vulgaris</i>
Brassicaceae	<i>Sisymbrium officinale</i> <i>Capsella bursa-pastoris</i>
Caryophyllaceae	<i>Spergula arvensis</i> <i>Stellaria media</i>
Fabaceae	<i>Trifolium repens</i> <i>Medicago lupulina</i>
Oxalidaceae	<i>Oxalis stricta</i>
Poaceae	<i>Digitaria ischaemum</i> <i>Digitaria sanguinalis</i> <i>Echinochloa crus-galli</i> <i>Elymus repens</i> <i>Panicum capillare</i> <i>Panicum dichotomiflorum</i> <i>Setaria glauca</i> <i>Setaria viridis</i>
Plantaginaceae	<i>Plantago major</i> <i>Veronica</i> sp.
Polygonaceae	<i>Fallopia convolvulus</i> <i>Persicaria maculosa</i>

stand density and delaying canopy development (Li et al., 2024). This reinforces the conclusion that effective pest management is a prerequisite for achieving intercrop benefits, especially in systems reliant on early-season synchrony between component species.

### 4.3 | Weed suppression in pea-mustard intercropping: The role of crop density and allelopathy

Our findings demonstrate that pea-mustard intercropping provides robust weed suppression, mediated primarily by increased total crop density and canopy structural complementarity. High-density mixtures (e.g., P1.5:M1.5) were the most effective, consistent with ecological theory that higher crop density increases competitive asymmetry against weeds by reducing available light, nutrients, and space (Weiner et al., 2010). The architectural complementarity between the upright mustard and the spreading pea canopy creates a multilayered structure that rapidly closes the canopy and restricts light penetration—an established mechanism for weed suppression in diversified systems (Lithourgidis et al., 2011).

The inclusion of mustard adds a secondary mechanism: allelopathy. Brassica species release glucosinolate-derived isothiocyanates, which inhibit germination and seedling growth of many weed species (Jabran et al., 2015; Weston & Mathesius, 2013). Although allelochemicals were not directly measured in this study, the strong weed suppression in high-mustard treatments supports the likelihood of interactive effects between physical shading and allelopathic interference—an increasingly documented phenomenon in Brassica-based multifunctional cropping systems (Haramoto & Gallandt, 2005).

From a practical standpoint, achieving strong weed suppression requires sufficiently high seeding densities for both crop components, especially in organic or low-input systems

where chemical weed control is limited. However, high-density intercropping increases the operational challenge of harvesting species with contrasting seed sizes. Farmers may require adjustments to combine settings or post-harvest cleaning systems, as demonstrated in recent work on mixed-species harvesting efficiency (Bailey-Elkin et al., 2022). Balancing agronomic benefits with harvest practicality remains essential for broader adoption.

## 5 | CONCLUSIONS

Intercropping field pea with brown mustard at recommended or higher seeding rates (1.0× and 1.5×) consistently outperformed sole cropping across four site-years in Atlantic Canada. These seeding ratios resulted in greater seed yields for both crops, LERs ranging from 1.48 to 1.78, and up to 62% reduction in weed biomass (at 1.5×:1.5×), potentially due to mustard's allelopathic effects and improved canopy coverage. In contrast, low seeding rates (0.5×) reduced pea and mustard yields by 38% and 33%, respectively, likely because of excessive interspecific competition. Significant site-year × treatment interactions underscore the influence of environmental conditions and biotic stresses (e.g., flea beetle damage in 2022), though intercrop benefits remained consistent in most cases. Overall, pea-mustard intercropping at recommended or higher densities offers a practical, low-input approach to enhance land-use efficiency, suppress weeds, and promote sustainability in maritime agroecosystems. Future research should explore nitrogen management, rotational benefits, and economic feasibility at commercial scales.

## AUTHOR CONTRIBUTIONS

**Qianwen Gong:** Formal analysis; methodology; writing—original draft; writing—review and editing. **Claude Caldwell:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **Tudor Borza:** Investigation; methodology; writing—review and editing. **Aaron Mills:** Methodology; writing—review and editing. **Ningbo Zeng:** Writing—review and editing. **Niran Foster:** Methodology; writing—review and editing. **Yunfei Jiang:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—original draft; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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## SUPPORTING INFORMATION

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