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Feed grain polycultures mitigate weather risk, support arthropods, and suppress weeds in the Western Corn Belt

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A R T I C L E I N F O

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Grain legumes
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A B S T R A C T

Ensuring sustainable food production while preserving biodiversity and ecosystem services under extreme weather is a challenge. We evaluated whether intercropping could enhance the yield, feed quality, and stability of crop production while also provisioning habitat for beneficial arthropods which could improve ecosystem services like pest predation. The study was conducted across two weather contexts at Brookings, SD, in 2023, with Planting A being cooler at germination, warmer at flowering, and generally drier than Planting B. Treatments included oat and pea monocultures, an oat-pea biculture, and in Planting A, an oat-pea-flax triculture. Overall grain yields were 2247 ± 151 kg ha^{-1}, 2498 ± 109 kg ha^{-1}, and 1423 ± 158 kg ha^{-1} for oat-pea, oat, and pea, respectively. Yields of monocultures varied between the two weather contexts, with 30.4 % and 113 % higher yields of oats and peas in Planting B versus Planting A. However, the biculture yields were not different across weather conditions ($p = 0.3$). The bi- and tri-cultures were at least as land-use efficient as monocultures while providing stable productivity and feed quality even under heat-stressed conditions. The oat-pea mix also had higher crude protein, similar acid detergent fiber and total digestible nutrient, and lower neutral detergent fiber content versus the oat grain, while pea had the highest crude protein and lowest fiber content. Both polycultures improved the habitat for predatory arthropods and effectively suppressed weeds. Our findings suggest that intercropping could improve the productivity, stability, and long-term sustainability of feed grain production.

1. Introduction

The continued trend of an increasing human population has led to a higher demand for land resources (Bitew et al., 2021), which is amplified by crop failures caused by climate variability and pest infestations (Raseduzzaman, 2016). Additionally, insect pests, diseases, and weeds have become more prevalent, and soil quality has deteriorated due to intensive agricultural practices such as monocropping with improved varieties (Chandra et al., 2011) and excessive use of inorganic fertilizers and pesticides (Malézieux et al., 2009). Producing more food to alleviate world hunger while conserving biodiversity and ecosystem services is a significant challenge for sustainable food production (Kremen and Merenlender, 2018; Boetzl et al., 2023; Yang et al., 2024). Therefore, a highly productive, climate-resilient, sustainable, and land-efficient cropping system is urgently needed to feed the growing global population and ensure a healthy environment (Tamburini et al., 2020).

Intercropping multiple crop species, including legumes with non-leguminous crops, could address these food production and environmental sustainability challenges (Agegnehu et al., 2008; Jensen et al., 2020; Dvořák et al., 2022). When executed carefully in certain conditions, intercropping may provide short-term benefits to crop yield and quality while promoting long-term sustainability and ecosystem services, such as water and soil quality (Gurr et al., 2003). These include higher and more stable grain yield, improved land use efficiency, and enhanced nutritional value (Bedoussac and Justes, 2010; Bedoussac et al., 2015; Hu et al., 2016; Yu et al., 2016; Su et al., 2018; Timaeus

Abbreviations: LER, Land equivalent ratio; GLMs, Generalized linear models; GDD, Growing degree days; CP, crude protein; ADF, Acid detergent fiber; NDF, Neutral detergent fiber; TDN, Total digestible nutrient; RFV, Relative feed value; ME, Metabolizable energy; NEg, Net energy of gain; NEm, Net energy of maintenance; NEl, Net energy of lactation; DE, Digestible energy.

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et al., 2021; van der Werf et al., 2021) compared to individual crop species. Intercropping typically includes a mixture of crop species with different functional traits, including rooting abilities, canopy structures, heights, and nutrient requirements, which are selected based on component crops' ability to complementarily utilize resources, such as light, water, and nutrients (Lithourgidis et al., 2011). Cereals and legumes are often mixed to produce relatively high yields of cereals while taking advantage of atmospheric N inputs fixed by legumes (Hauggaard-Nielsen et al., 2009). Additionally, cereals can reduce lodging in pea by providing mechanical support, which aids harvest, improves quality, and reduces disease pressure (Trenbath, 1993; Finckh et al., 2000; Banik et al., 2006; Bedoussac and Justes, 2011; Kontturi et al., 2011; Cutforth et al., 2013; Podgórska-Lesiak and Sobkowicz, 2013; Jevtić et al., 2023). Oats specifically establish faster and develop deeper roots than pea, allowing them to absorb nutrients from deeper soil layers. Intercropping can also improve weed management and enhance arthropod communities, improving crop resistance to biotic stress. For example, intercropping legumes can increase cereal yield by 15–25 % by suppressing the attack of insect pests, diseases, and weeds (Kumar et al., 2020; Kumawat et al., 2022). Wheat (*Triticum aestivum* L.) and chickpea (*Cicer arietinum* L.)-intercropping can reduce weed biomass and weed population by about 58–70 % over monoculture wheat (Banik et al., 2006; Gu et al., 2021). Furthermore, intercropping flowering legumes and cereals may improve habitat for beneficial arthropods – both predators and pollinators – that enhance overall ecosystem services and plant health (Boetzl et al., 2023). While intercropping has potential to meet many of the demands placed on agricultural systems, incorporating them into mechanized systems such as the US Corn Belt remains a challenge.

We evaluated oats (*Avena sativa* L.), field pea (*Pisium sativum* L.), and flax (*Linum usitatissimum* L.) mixtures for their potential agronomic, climate adaptation, and ecosystem services benefits across contrasting weather patterns. While oat-pea intercrops are regularly utilized in annual forage production systems to enhance forage quality (e.g. Carr et al., 2004), their use for grain production is comparatively rare. Unlike in forage production, grain production adds agronomic challenges of matching maturity windows and ensuring grain can be separated if the end use requires. Still, experience from growers in the Canadian plains, which are significantly cooler and drier than the region of this manuscript, suggest the productivity benefits can be substantial enough to overcome agronomic challenges (Mbanyele et al., 2024).

Our goal was to identify the potential of cereal-legume intercrops to increase feed grain production, quality, and production stability over a monoculture within the western Corn Belt, while also enhancing habitat for predatory arthropods. We intend this as a first step toward developing regionally relevant intercrop management studies. In the western Corn Belt, the major crops are corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.), both of which are used primarily as animal feed or biofuel feedstock, whereas milling grain for human consumption is less prevalent. Still, this region is a center of oat production and adjacent to a center of field pea production (USDA-NASS, 2024). We hypothesized that the oat-pea system would be more productive in terms of land equivalent ratios and feed value than either oat or pea monocultures, and this productivity would be more stable across weather patterns compared to monocultures. We further expected that the oat-pea system would support a greater number and diversity of arthropods, including predators, and suppress weeds as effectively as herbicide applications. Finally, we expected that incorporating flax would further improve ecosystem services and the quality of feed production and arthropod habitat without hurting productivity. Our results highlight the potential for synergies between land-use efficiency, feed grain stability, and pest and weed management in this system, and thus reveal avenues for further research to support the adoption of this cropping system.

2. Methods

2.1. Study description

The study was performed within two rainfed weather contexts in 2023 at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota (44º 19' N, 96º 46' W; 500 m elevation). Soils at the research farm are Barnes clay loam (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) with nearly-level topography, relatively high soil organic carbon (18 g C kg^{-1} soil, 0–15 cm), and 280 g kg^{-1} clay measured in the top 5 cm. Previously, the field was managed as no till with synthetic fertilizer and herbicide applications, with crops being: 2019 – corn; 2020 – soybean; 2021 – spring barley (*Hordeum vulgare* L.); 2022 – soybean.

The study was designed as a split plot design with four replicates. Main plots were planting date, either April 27th or June 1st. We denote these dates as Plantings A and B, respectively, to emphasize that they should not be considered treatments of agronomic interest; in this region, best management of both oats and peas is to plant as soon as possible in the spring (Endres and Kandel, 2021; Karki, 2022). Instead, they were selected to subject the crops to different weather conditions at critical growth stages (Fig. 1) while controlling soil properties. Subplots consisted of crop mixtures in 6.5 m x 19.3 m plots. The split plot arrangement was selected to increase power to detect changes of the planting date * cropping system interaction and the cropping system main effect.

The cropping systems were an oat (var. Reins) monoculture, a pea (var. Delta) monoculture, an oat-pea polyculture, and for the earliest planting date, an oat-pea-flax (var. AAC Bright) polyculture. Oat and pea varieties were selected for morphological and phenological considerations. Reins oat was chosen to minimize competition with pea; it is early maturing, semi-dwarf, and has an upright, open canopy architecture (Kolb et al., 2017). Delta pea was selected to tolerate oat competition; it is a semi-leafless, semi-dwarf variety that is adapted to dryland, semi-arid conditions (Chen et al., 2008). Plots were planted in separate passes using a John Deere 1590 no-till drill with 19 cm row spacing. Detailed agronomic information is available in Table 1. Of note, pea plots received pre-emergence applications of broad-spectrum and residual herbicides and a single, in-season application of grass-selective herbicide due to high populations of grassy weeds at this location. This management ensured that weed pressure did not hinder pea growth and development, ultimately leading to an otherwise-avoidable reduction in yield. No fertilizer was applied due to generally adequate soil fertility.

2.2. Data collection and calculations

Stand count, plant biomass, weed biomass, grain yield, arthropods, and nutritive values were monitored. Stand count of each species was measured using four, 1.00 m sections of row per plot at 100 % emergence, approximately one week after initial emergence but before the onset of oat tillering. Aboveground biomass was hand-harvested from the southern half of each plot in four, 1.00 m row sections at maturity using electric lawn shears. These sampling locations were at least 1.0 m from plot edges and preserved the northern half for accurate, full-plot yield estimates. Biomass was separated by oat, pea, flax, and weeds in the field and dried for at least 48 hours at 70°C or until no further change in weight was observed. Mature biomass was weighed and threshed to separate the grain, using a thresher (Small Bundle Thresher, ALMACO, Nevada, Iowa, USA) for the oats, and by hand for the peas. The flax grain was disregarded as it did not fully mature before harvest. Grain was cleaned using a seed blower and weighed. Grain yield was adjusted to 13 % moisture content. Grain samples were sent to Ward Laboratories Inc. for nutritive value analysis (Wet chemistry Analysis: F-5. Protein & RFV, Ward Laboratories, Inc., Kearney, Nebraska, USA) (Ward, 2020).

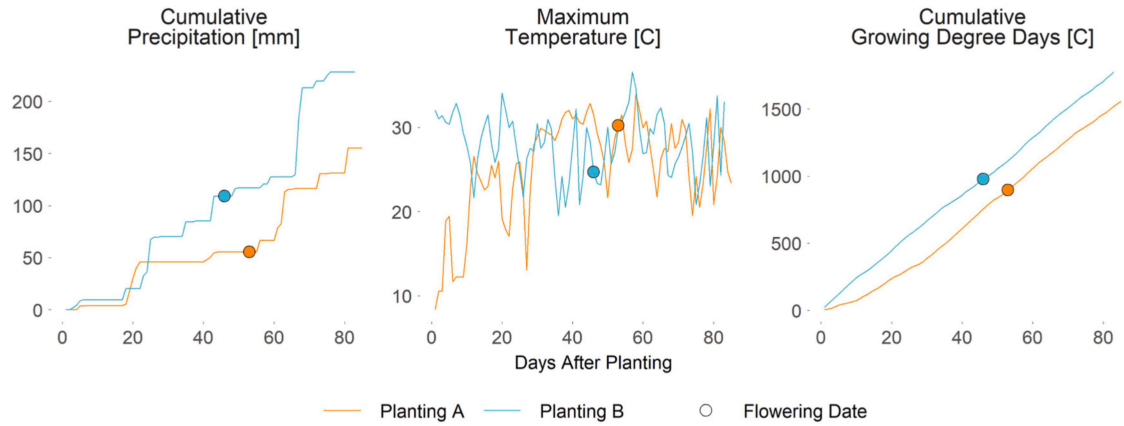

Fig. 1. Weather conditions during the growing season: cumulative precipitation (mm), maximum daily temperature (°C), and growing degree days (GDD; base = 0°C) at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota, USA. Dots indicate the dates of oat flowering while colors differentiate planting dates A (orange) and B (blue).

Table 1
Crop specific agronomic information for each cropping system grown at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota in 2023 (two planting dates).

Activities	Planting	Cropping systems				
		Oats	Peas	Flax	Oat-pea	Oat-pea-flax
Crop cultivars		Reins	Delta	AAC Bright		
Target population (plants ha^{-1})		2.97 million	803 thousand	7.4 million		
Seeding rate (kg ha^{-1})		112	168	50		
Mixing ratio		100	100	-	50:75	50:75:50
Seeding depth (cm)		2.54–3.81	2.54–3.81	2.54–3.81		
Planting date	Planting A	April 24, 2023	April 24, 2023		April 24, 2023	April 24, 2023
	Planting B	June 1, 2023	June 1, 2023		June 1, 2023	
Fertilizer application	Planting A	Not applied.				
	Planting B	Not applied.				
Herbicide application	Planting A	Applied pre-emergence herbicide was applied to pea only; with a mixture of Spartan FL (Sulfentrazone) @ 0.28 kg ha^{-1}, Roundup PowerMAX 3 @ 1.40 kg ha^{-1}, and Ammonium Sulfate (AMS) @ 4.68 L ha^{-1}. Post-emergence herbicide was applied to pea only; with a Select Max (Clethodim) @ 1.12 kg ha^{-1}, AMS @ 4.68 L ha^{-1}, and Nonionic Surfactant (NIS) @ 0.9 kg ha^{-1}.				
	Planting B	Applied pre-plant herbicide was applied to all crops; with a mixture of Roundup PowerMAX 3 @ 1.40 kg ha^{-1}, and Sharpen @ 0.14 kg ha^{-1}, AMS@ 4.68 L ha^{-1}, and Methylated Seed Oil (MSO) @ 0.9 kg ha^{-1} Post-emergence herbicide was applied to pea only; with a Select Max (Clethodim) @ 1.12 kg ha^{-1}, AMS@ 4.68 L ha^{-1}, and NIS @ 0.9 kg ha^{-1}.				
Harvest date	Planting A	July 17, 2023 (hand harvested) and July 26, 2023 (plot combine harvested)				
	Planting B	August 22, 2023 (hand harvested) and August 23, 2023 (plot combine harvested)				

We assessed productivity as both yield and land equivalent ratios (LER). LER is the sum of the relative yields of component species in the mixture compared to the pure stand. An LER > 1.0 indicates a per-area yield advantage (overyielding) of the mixture over monocultures of the component species. The LER was computed as (van der Werf et al., 2021; Li et al., 2023):

$$LER = \sum_{i=1}^{n} Y_i M_i^{-1} \quad (1)$$

Where Y and M are the yields of crop i in the n-species polyculture and monoculture, respectively.

Arthropods were studied for abundance, richness, and potential pest predation. Communities were sampled in the morning (0900) and afternoon (1300) of June 15th, seven weeks after first planting. We focused solely on Planting A as this was phenologically most realistic for evaluating arthropod responses. Arthropods were collected by moving an inverted leaf blower (Husqvarna 125BVX) across crops for 60 seconds while walking in a straight line through the middle of each plot (Prather et al., 2020; Welti et al., 2020). Samples were transferred to zip-top bags, placed in a cooler, and kept frozen until sorting. Arthropod specimens were pooled from the two sample periods per plot, and then counted and identified to morphospecies, which provides reliable estimates of species richness (Oliver and Beattie, 1996; Roeder et al., 2018).

Predation of pest species was measured in each plot after arthropod collection using a previously designed sentinel prey station (Roeder and Harmon-Threatt, 2022) comprising ~50 corn earworm eggs (*Helicoverpa zea* Boddie) glued to an index card that was placed in a small petri dish within a vertebrate exclosure. The exclosure was created from a suet bird feeder cage (14.2 cm × 12.2 cm × 4.6 cm) wrapped with metal mesh that had 0.635 cm × 0.635 cm square openings. For each sentinel prey station, eggs were counted prior to deployment in the field and then counted again after 48 hours to determine the proportion that had been consumed. Similar methods have been used in other agronomic studies to rapidly assess one facet of ecosystem services that insects provide (Werling et al., 2011; Helms IV et al., 2020).

2.3. Analysis

All analyses were performed in *R* 4.3 (R Core Team, 2023). Mixed effects models of all measurements were evaluated using *lme4* 1.1 (Douglas Bates et al., 2015). Because weather stability was a central hypothesis, these models included fixed effects of crop mixture, planting day, and the interaction between these. Block and planting date by block were included as random intercepts. Most parameters were analyzed with standard, linear mixed effects. We evaluated if arthropod abundance, species richness, and predation of pest species differed across treatments using generalized linear mixed effects models (GLMMs). We included crop mixture as a fixed effect and block as a random effect in the GLMMs as planting day was not studied for these measurements. We used a negative binomial distribution for overdispersed abundance data, a Poisson distribution for species richness, and a binomial distribution for the proportion of pest species eggs that were consumed (i.e. predation). Weed biomass was log-transformed prior to analysis to ensure normally distributed residuals. Model terms were tested with analysis of variance using *car* 3.1 (Fox and Weisberg, 2019). Pairwise contrasts among treatments were performed using *emmeans* 1.10, with false discovery rates controlled at $p = 0.05$ (Lenth, 2025). Code is included in the data repository indicated below.

3. Results

3.1. Growing conditions and maturity

To test whether the oat-pea polyculture was more resistant to weather variation than either monoculture, we used planting date to impose different weather conditions within the same field. Validating this experimental approach, Planting A was cooler and wetter than Planting B during early development, while it was substantially warmer and drier at flowering compared to cooler and wetter Planting B (Fig. 1), which influenced crop yields (Fig. 2). Because oat and pea development is heat-sensitive (Miller et al., 2001), this resulted in approximately one-week slower vegetative development in Planting A versus Planting B. Oats and peas flowered around 50 and 45 days in Planting A and Planting B, respectively. The third week of May to the third week of June

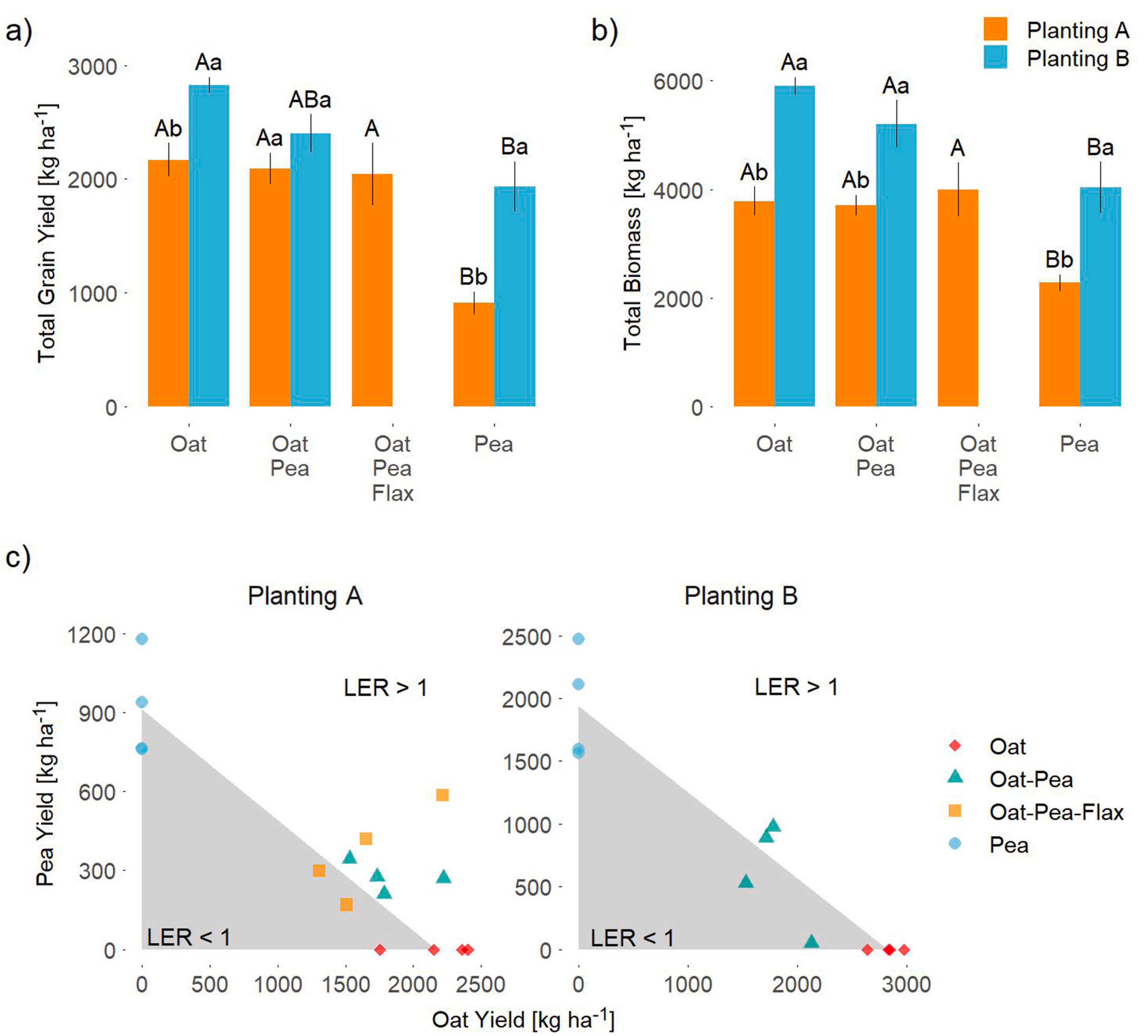

Fig. 2. Weather effects on grain yield and biomass productivity: a) total grain yield (kg ha^{-1}), total biomass productivity (kg ha^{-1}) and c) land equivalent ratio (LER) of oats, pea monoculture and their mixture grown at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota, USA. In a) and b), colors indicate planting dates A (orange) and B (blue), while letters indicate significant ($p < 0.05$) differences among treatments within planting date (uppercase) and differences between planting dates within treatment (lowercase). In c), colors and shapes indicate treatment of oat (red diamonds), pea (blue circles), oat-pea (green triangles), and oat-pea-flax (orange squares). The regression line connects mean yields in oat and pea monocultures.

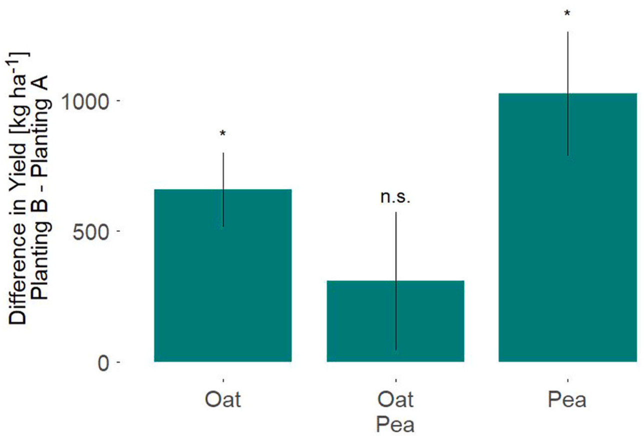

Fig. 3. Stable yields of polyculture across weather. Grain yield difference of oat, pea monoculture and their mixture grown at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota, USA. * indicates difference from zero at $p < 0.05$ using a *t*-test. n.s. indicates no significant difference from zero.

was warmer compared to late June and the entire month of July. This drier and warmer weather coincided with the flowering and grain-filling stages of Planting A compared to wetter and cooler weather during the flowering and grain-filling stages of Planting B, which hastened grain maturity in Planting A. Ultimately, all oat and pea crops matured around 84 days after planting across planting dates.

In addition to weather, cropping system altered pea development but not oat development. In both planting dates, pea matured 7–10 days earlier in polyculture than monoculture. Flax did not affect either oat or pea maturity. The flax variety selected did not mature quickly enough to produce dry seed by the time oats and pea were ready to harvest.

3.2. Agronomic performance and stability

Variations in growing conditions translated to differences in crop yield ($p < 0.0001$, Fig. 2), with yields consistently higher in Planting B than in Planting A. The oat monoculture produced the most grain overall (2500 ± 110 kg ha^{-1}), and the pea monoculture produced the least grain (1420 ± 160 kg ha^{-1}). Both monocultures also showed substantial variation in yield between the growing conditions, with the warmer, wetter Planting B conditions translating to 30.4 % and 113 % higher yields of oat and pea, respectively (oat $p < 0.0001$; pea $p = 0.0001$). In contrast, with the monocultures, the oat-pea mix yields were not affected by planting dates (Δyield $= 310 \pm 270$ kg ha^{-1}; $p = 0.326$), and yields in Planting A were not lower than oat monoculture yields (Δyield $=77 \pm 17$ kg ha^{-1}; $p = 0.98$). Flax did not affect oat-pea polyculture yields despite its failure to reach maturity (Δyield $=50 \pm 170$ kg/ ha^{-1}; $p > 0.99$) (Fig. 2, Table 2, Table S1).

In addition to its stability and productivity across weather conditions, the oat-pea mixture displayed qualitative potential to overyield under adverse weather conditions. In the less favorable weather of Planting A, the mixture performed at a land equivalent ratio of 1.16 ± 0.09 ($p = 0.16$). While the mixture did not overyield in Planting B, it also did not underyield (LER $= 1.0 \pm 0.1$; $p = 0.64$). Combined, these results indicate that the oat-pea mix is at least as productive as monocultures in terms of land use efficiency and better maintains productivity in hot, dry conditions, which may lead to overyielding under those conditions.

3.3. Grain feed value between cropping systems

Analysis of grain feed value provided a complementary window to the productivity of the oat-pea mixture. Critical feed components, crude

Table 2
p-values of treatment effects on measured variables.

	Crop	Planting	Crop × Planting
Yield	**< 0.001**	**0.026**	0.073
Crop Biomass	**< 0.001**	**0.007**	0.611
LER		0.203	
Oat Yield	**< 0.001**	0.066	**0.003**
Pea Yield	**< 0.001**	**0.02**	**0.002**
Ratio		**0.042**	
CP	**< 0.001**	**0.036**	**0.001**
TDN	**< 0.001**	0.724	0.279
ADF	**< 0.001**	0.688	0.236
NDF	**< 0.001**	0.821	0.15
Egg Predation	**< 0.001**		
Bugvac Richness	**0.004**		
Bugvac Abundance	**< 0.001**		
Weed Biomass	0.092	0.427	0.607

Abbreviations: CP - Crude Protein; TDN - Total Digestible Nutrients; ADF - Acid Detergent Fiber; NDF - Neutral Detergent Fiber

protein content (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and total digestible nutrients (TDN) varied significantly among different crops ($p < 0.0001$). However, the influence of planting date and the interaction of the crops by planting date was detected only on CP (Fig. 4; Table S2). Across planting dates, the oat-pea mixture had 15.5 % higher CP than oats (oats: 146; oat-pea: 169 g kg^{-1}; $p = 0.001$); however, this value was significantly lower than peas by 41.2 % ($p < 0.0001$). Relative to oat grain alone, the oat-pea mixture had lower NDF and digestible energy (DE; megacalorie kg$-^{1}$), and equivalent CP, ADF and TDN (Table S2). Pea alone had higher CP and TDN but lower energy content and fiber than either oats or the intercrop mixture.

3.4. Grain yield, biomass production and grain feed quality between planting dates

Weather affected the production of crop biomass and grain as well as the grain quality as feed. Specifically, in the drier Planting A, oat grain production was relatively high, but pea yields were reduced by 53 % compared to wetter Planting B (Fig. 2a). The composition of the mixed grain in the intercropped system was 873 g oats and 123 g peas per kg of the mixture in Planting A, but 690 g oats and 310 g pea per kg mixture in Planting B. While the relative high productivity of oat compensated for reduced pea yields in determining overall yields, the combined flexibility of this oat:pea grain ratio and the nutrient content of oat and pea grain together enhanced the stability of feed quality of the mixed grain across weather patterns (Fig. 4; Table S2). Despite the differences in oat:pea grain ratios, the mixed grain harvested from Planting A was not different in protein ($p = 0.4$) or fiber content (ADF: $p = 0.58$; NDF: $p = 0.81$) than that of Planting B, suggesting that oat-pea mixed grain may perform similarly across weather patterns despite different oat:pea grain ratios. Biomass (i.e., hay) production differed significantly between crops ($p = 0.0003$) and planting date ($p = 0.007$); however, there was no interaction between crops and planting date ($p = 0.61$) (Fig. 2b; Table S1). The hay production for each cropping system was higher in planting B than in Planting A. We found the oat-pea hay production was similar to oat monoculture hay across weather patterns: both crop dates produced 3700–4000 kg ha^{-1} biomass in Planting A and 5200–5900 kg ha^{-1} biomass in Planting B (Fig. 2b). While we did not assess hay quality, pea is well-known to improve the protein and digestibility of oat hay (Chapko et al., 1991).

3.5. Arthropod habitat and weed pressure

We evaluated agronomic and ecosystem benefits that intercropping might hold over monocropping. First, we evaluated the arthropod habitat benefits that pea and flax added to oat grain systems. The study observed that morphospecies richness ($p = 0.004$), arthropod

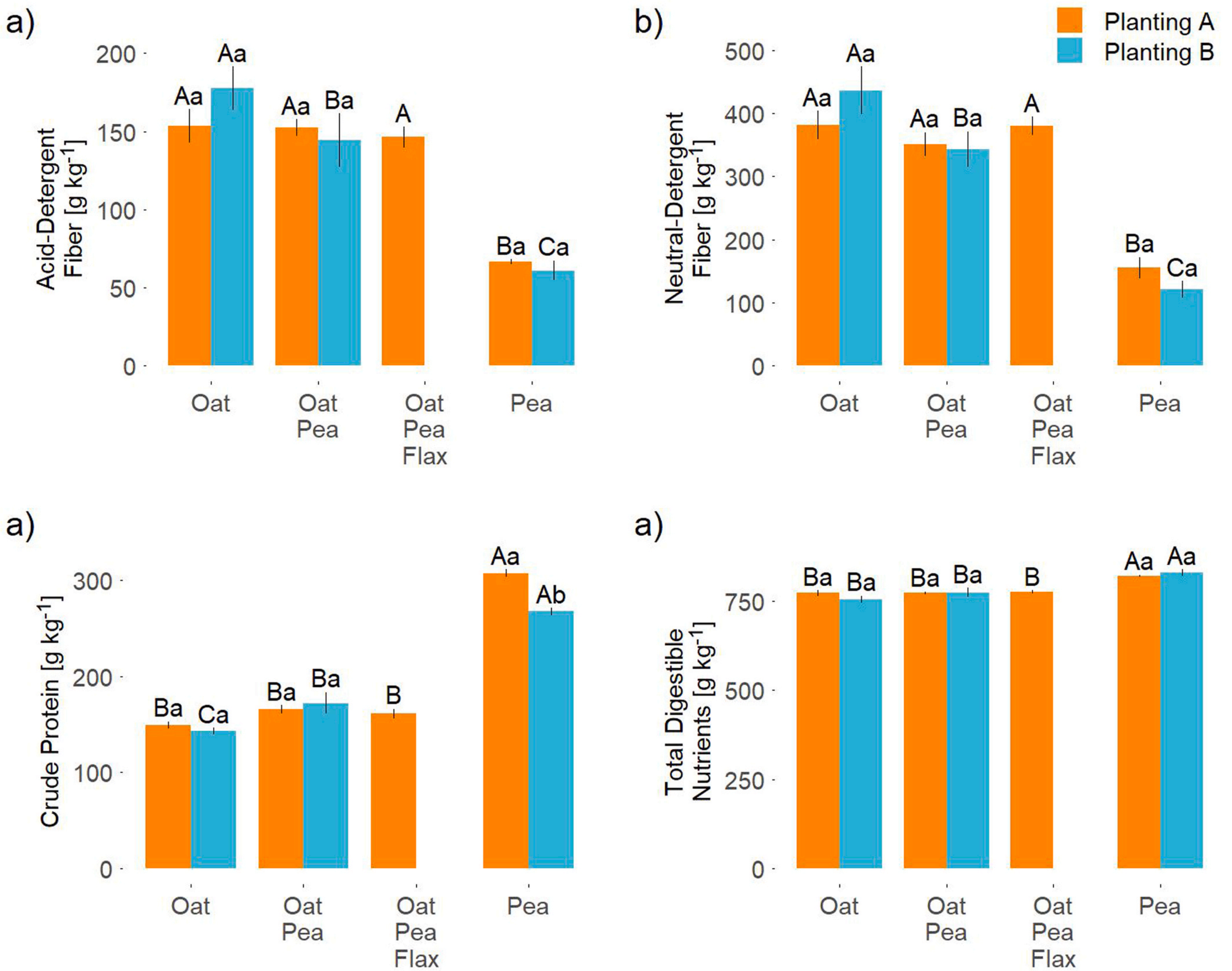

Fig. 4. Nutritional components of grain. a) acid-detergent fiber concentration (g kg^{-1}), b) neutral-detergent fiber concentration (g kg^{-1}), c) crude protein concentration (g kg^{-1}), and d) total digestible nutrient concentration (g kg^{-1}) of grain from each cropping system grown at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota, USA. Colors indicate planting dates A (orange) and B (blue), while letters indicate significant ($p < 0.05$) differences among treatments within planting date (uppercase) and differences between planting dates within treatment (lowercase).

abundance ($p < 0.0001$) and egg predation ($p < 0.0001$) varied significantly depending on the crop mixture (Fig. 5). Morphospecies richness was consistently higher in plots containing oat than in pea monoculture (Fig. 5a), while arthropod abundance was highest in all mixed-species crops (Fig. 5b). Egg predation levels were highest in polycrops, averaging 70.2 ± 19.1 %. While this predation level was not statistically different in oat-pea than in the pea monoculture (53.6 ± 18.2 %), it was higher than egg predation in the oat monoculture (26.7 ± 5.6 %), indicating improved habitat for ground-dwelling predators that may suppress pests (Fig. 5c).

Second, we evaluated weed pressure across cropping systems and planting dates. We found no significant difference in weed biomass either across planting dates or among cropping systems, despite the application of herbicide to the pea monoculture ($p = 0.09$). This indicates that oats effectively suppressed weeds within pea, allowing pulse production with reduced herbicide application (Fig. 5d).

4. Discussion

A main goal of intercropping is to improve the cropping systems' yield, quality, and stability over monocultures. Our results align with these goals, as monocultures performed differently depending on weather whereas the intercrop produced stable yields across weather that equaled or exceeded those of monocrops. We also found additional value from the intercrop: Grain feed quality was higher than oat monocultures, and arthropod abundance and diversity indicators were greater in the intercrop (Table S2, Fig. 4, Fig. 5).

These results highlight the potential of polycultures to enhance yield stability, plus additional benefits that polycultures may provide to this region including a non-chemical approach for managing weeds, insects, pests, and diseases. Further studies may investigate mechanisms for these benefits, including root complementarity traits of the mixture and canopy physical structure that is favorable for arthropod habitat (Langellotto and Denno, 2004; Beillouin et al., 2021; Roeder and Harmon-Threatt, 2022; Księżak et al., 2023). Conducting multi-year and multi-location trials under the same management conditions would provide a more nuanced picture of the intercropping system as a strategy for crop diversification, which could lead to more sustainable agricultural production.

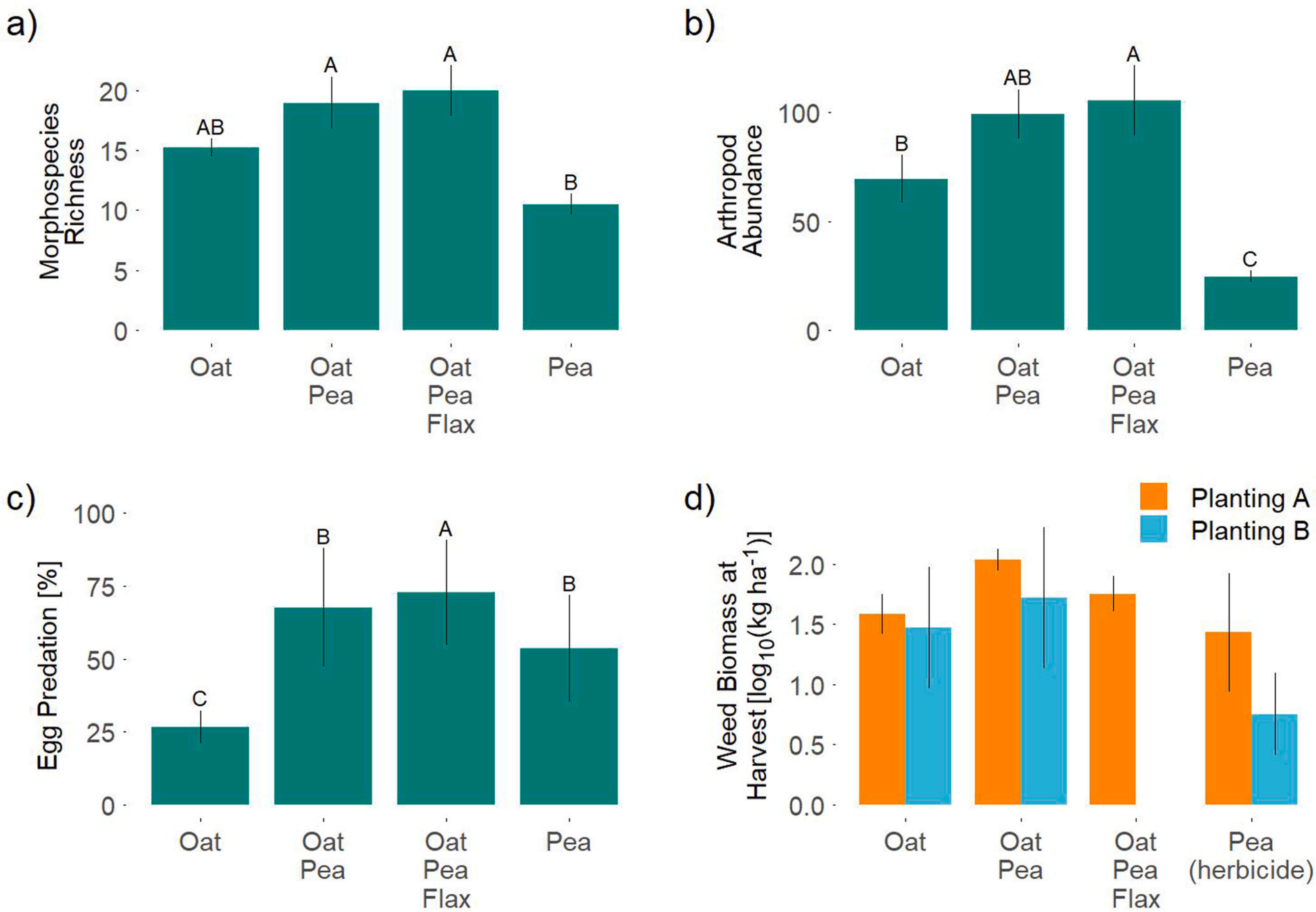

Fig. 5. Agronomic and ecosystem benefits from polyculture: a) Morphospecies richness, b) arthropod abundance, c) egg predation (%) and d) weed biomass at harvest of oat, pea monoculture and their mixture grown at the Eastern South Dakota Soil and Water Research Farm in Brookings, South Dakota. Panels a-c were collected on Planting A only; in panel d), colors indicate planting treatments A (orange) and b (blue). In-season herbicide was applied to pea only. Letters denote differences among treatments at $p < 0.05$.

4.1. Weather conditions affected phenology, yield, and grain quality

Long-term studies in this region have found that warmer temperatures in the early vegetative growth stage favor oat yields, while more moisture during grain fill favors pea yields (Ewing et al., 2024). The early planting date (Planting A) had cooler and drier conditions than the late planting date (Planting B) during vegetative growth (Fig. 1). As a result, the growth and development of the earlier planted crops were slower, with the flowering and maturity stages also delayed. The lower yields of crops, including the mixtures in Planting A, could be attributed to high temperatures and dry conditions during flowering and grain filling compared to Planting B (Fig. 1) (Hellewell et al., 1996; Bueckert et al., 2015). Additionally, during the vegetative growth stage, both crops compete for water and nutrients, affecting their growth and development, and overall yield. Finally, plant regulation mechanisms for heat and drought stress differ among crop species, growth stages and intercropping systems, ultimately reducing yields of cereals, legumes, and oil seeds (Zhang et al., 2013). For instance, higher temperatures during the vegetative stage can cause morphological damage, reduce chlorophyll content, and lower photosynthetic rates and leaf water content in canola, leading to poor growth and lower seed yields (De la Haba et al., 2014; Ahmad et al., 2021). Heat stress during the reproductive stage disrupts fertilization (Xi, 1991), negatively affecting pollen viability and the functionality of reproductive organs (Ihsan et al., 2019). Furthermore, high temperatures impair metabolic functions, such as light interception and carbon assimilation (Maestri et al., 2002), leading to significant yield losses in canola and cotton due to hindered pod and seed development (Ekinci et al., 2017; Pokharel et al., 2020). This suggests that temporal complementarity is essential when selecting the crop species and planting time in cereal/legume cropping systems. This choice might influence the microenvironment, plant-plant interactions, and grain yield (Zhang et al., 2015; Engbersen et al., 2021; Raza et al., 2023). Leveraging these strategies is increasingly important for adapting agriculture to extreme weather patterns, including heat waves and drought, that climate change is exasperating (Gowda et al., 2018).

4.2. Intercropping affected grain yields and stability across different weather conditions

These different weather conditions corresponded with qualitatively different benefits of intercropping. Our study found that the oat-pea intercrop of Planting B had an LER of 1.0 while Planting A had an LER of 1.16. However, we did not find a significant difference between these two values, and Planting A was not statistically larger than 1.0, which suggested the consistent yield between intercrop mixture and monoculture (Fig. 2**c).** The lower LER value in the current study could be due to the non-application of fertilizers in the plots; for example, a recent meta-analysis of intercropping systems revealed that non-fertilized experiments had a lower LER value of 1.14 compared to fertilized plots, with a higher LER value of 1.26 (Zustovi et al., 2024). LER benefits of the oat-pea system seem to be more context dependent than other intercrops, as 70 % of the oat-pea intercrop studies reported an LER value of < 1 (Mbanyele et al., 2024). In contrast, maize and soybean intercropping demonstrate up to 50 % better land and water-use efficiency compared to sole cropping, likely due to improved light and water-use efficiency from reduced intraspecific competition. This helps in optimizing resource utilization and may enhance soil fertility through nitrogen fixation (Raza et al., 2022). Management also affects intercropping productivity. The proportion of components in an intercrop significantly impacts the total grain yield of the intercropping systems. For example, when intercropping small grain and pulses, a higher proportion of small grain in the mixture resulted in a 40 % increase in grain yield compared to the sole crop (Haymes and Lee, 1999); however, when grain-pulse mixtures are relatively rich in pulses, yield tend to be lower than small grain yields alone (Ofori and Stern, 1987). Our study used a higher proportion of peas in the mixture (Table 1), which could be responsible for oat-pea intercrop's lower or comparable yield to that of oat monoculture. Still, on a land-equivalent basis, we found the intercrop performed as well or better than monocultures.

Complementing a potential increase in productivity, intercropping provided consistent yields under varying environmental conditions. A meta-analysis reported that intercropping could decrease crop failure and increase crop yield stability over time and across different locations (Raseduzzaman and Jensen, 2017). Our study supports the findings from this study, suggesting that individual components in the mixture could compensate for the loss during unfavorable weather conditions. One potential mechanism is different weather responses of oat and pea. For example, a long-term study from the same location observed that oat yields and pea yields were uncorrelated because they do best under different conditions despite having the same phenology (Ewing et al., 2024). Still, both oat and pea monoculture yields were lower in Planting A than Planting B, suggesting additional, stabilizing effects of intercropping. For instance, we had comparatively lower yield of peas in the mixture in Planting A, but a higher grain yield of oats which compensated for the reduced pea yield, leading to consistent yields of the mixture. This phenomenon may be linked to the species complementarity effect, where the legume's biological nitrogen fixation and the cereal's intense competition for soil nitrogen may synergize to increase yield and grain quality (Li et al., 2020; Bremer et al., 2024). To sum up, this production consistency and land use efficiency speaks to the resistance and productive potential of the intercropping system under extreme weather.

4.3. Intercropping increases biomass production

Total mature biomass accumulation was similar to grain yield patterns. On average, across crops and planting dates, intercropping mixtures produced similar biomass to oats but higher biomass than peas (Table S1). These findings parallel those of (Raza et al., 2023), which suggested that intercrops of species with complementary morphologies and resource needs led to higher biomass accumulation. The complementary growth habits and diverse canopy structures of intercropping systems improve light interception, increasing biomass accumulation (Dutta et al., 2022).

4.4. Intercropping influences on grain feed quality

The energy and nutritive value of feed requirements vary based on several factors, such as the type of animal (cattle, pigs, and poultry), the feed ingredients (oats, peas, soybean), the environment, and methods of preparation (Noblet et al., 2022). Peas and oats have distinct contributions to balanced rations: peas are rich in protein and total digestible nutrients, while oats are rich in starch and fiber (McCuistion et al., 2019). Mixing grain cereals and legumes with other feed sources is essential to balance protein and fiber for a given feed use (Berk et al., 2008).

Guidelines recommend a minimum of 16–17 % crude protein (CP), 20 % acid detergent fiber (ADF), and 28 % neutral detergent fiber (NDF) during the mid-lactation stage of dairy cattle and similar requirements for high-performing beef cattle (Linn et al., 2021). The CP and NDF from an oats-peas intercrop consistently met such requirements across planting dates, indicating a balanced protein and fiber content for lactating dairy cows, whereas oat was consistently low in CP and pea consistently low in ADF (Fig. 4, Table S2). Looking more closely at these nutritive components, when the CP:TDN ratio is less than 0.20, CP limits bacterial reproduction and growth, restricting the digestion rate of forage. However, when the CP:TDN ratio exceeds 0.20, the excess CP will be excreted as urea, increasing the energy cost to the animals and resulting in lower average daily weight gain or milk production (Rayburn, 2022). Similarly, excessive NDF reduces the level of milk production for dairy cows or rate of weight gain for beef cattle. High-producing dairy cows perform best with 35–55 % NDF and 19 % ADF to prevent milk-fat depression and maintain rumen health (Rayburn, 2022). The average CP content, CP to TDN ratios, and NDF values of oat-pea and oat-pea-flax intercrops in our polyculture study are near-ideal for a balanced ration for dairy cows and high performing beef cattle, suggesting a benefit of intercrop compared to monoculture species. (Table S2). Still, all grains grown in this study would require mixing with a higher-lignin feed to meet minimum ADF requirements.

A potential risk with intercropped grain is inconsistent quality across weather conditions, especially if certain conditions favor one species. Our results suggest that nutritive content of component grains also can vary across weather such that they minimize this risk. While we observed a two-fold higher oat:pea grain ratio in Planting A than Planting B, pea CP content was 15 % higher in Planting A, while oat ADF and NDF were higher by 16 % and 14.5 %, respectively, in Planting B (Table S2). The net result was consistent nutritional quality of the mixed grain. Overall, the oat-pea intercrop had more favorable CP and fiber content for ruminants compared to either monoculture. It also produced a consistent, balanced ration for ruminants straight from the field.

4.5. Intercropping influences on arthropod diversity and ecosystem services

In addition to food and feed, agriculture is increasingly called upon to improve environmental quality. Arthropods are important indicators of this; arthropod richness, abundance, and predation of pest eggs were all highest in the oat-pea-flax mixture compared to monocultures of either oats or peas (Fig. 5). One working hypothesis for such a result is that habitat structure and complexity increased with the number of crop species, providing additional area and microclimates for beneficial arthropods like ants, beetles, and spiders. Similar hypotheses have been proposed to occur in a variety of agricultural management schemes that include intercropping, cover crops, polycultures, and perennial agroforestry (Beillouin et al., 2021; Harrison et al., 2019; Iverson et al., 2014; Pierre et al., 2022; Roeder and Harmon-Threatt, 2022). This habitat improvement in polycultures was synergistic with high productivity and grain feed value versus monocultures. Likewise, a recent study that focuses on soil fauna in different crop-legumes intercropping and straw incorporation and conservation tillage scenarios, found that intercropping increased the density, biomass, and the diversity of euedaphic collembolans, and increased densities of acarid mites while reducing evenness. These findings demonstrate that intercropping benefits some species while potentially disadvantaging others, possibly impacting functional traits of arthropod communities (Liu et al., 2025). Together, these finding suggest crop diversity can have a significant impact on arthropods and the services they provide. Novel agricultural practices will need to be further developed and tested across a variety of ecosystems.

4.6. Intercropping influences on weed suppression capacity

Weed management is a critical component of cropping system viability. Pulses tend to be less competitive with weeds than cereals, as highlighted by our need to use in-season chemical weed control in pea monoculture plots. Encouragingly, we found no significant difference in weed biomass between intercrops and pure stands, despite herbicide use in pea plots (Fig. 5**d**). A higher proportion of cereals in mixes with legumes are more effective at suppressing weeds (Monti et al., 2019). Previous studies of similar polycultures found reduced weed density by creating unfavorable conditions for their germination and survival (Chikoye et al., 2001), thus reducing weed biomass by 56 % compared to monocultures (Verret et al., 2017). Consistently, intercropping oat-pea reduces weed populations by quickly producing biomass and improved ground cover that competes with weeds (Bailey-Elkin et al., 2021; Soujanya et al., 2024). Proposed mechanisms include resource complementarity between the intercrop components that allows for a higher resource capture than sole crops, leaving no or fewer resources available for weeds, which hampers their growth (Liebman and Dyck, 1993; Corre-Hellou et al., 2011). We observed consistently low weed biomass across both weather contexts, which suggests that oat-pea polycultures are consistently able to outcompete weeds for light, water, and nutrient resources. These results underscore the need for more extensive research to better understand the benefits of intercropping in weed suppression, which could have significant implications for agricultural practices, especially in organic systems.

4.7. Outstanding challenges

We found that intercropping offers several benefits, including yield stability, efficient use of land resources, improved habitat for predatory arthropods, and sufficient weed management. We also encountered several challenges in implementing this system, including finding suitable equipment for planting efficiently at optimal depths; identifying compatible herbicides for component crops; identifying the right crop varieties with traits that are suitable for the region and the intercropping systems; and developing strategies and management practices for biotic stressors. Despite these challenges, commercial farms in the Canadian Plains are implementing oat-pea intercrop systems for grain production, demonstrating the scalability of this system (Mbanyele et al., 2024). Working with growers and policy makers to develop new practices and economic incentives for transitioning from current practices is essential to validating and achieving these benefits. Addressing these multifaceted approaches would help implement a long-term sustainable agriculture production system.

A final caveat to this study arises from its design. Any cropping system must be analyzed in multiple environments to identify expected outcomes. Common approaches for this include multi-year studies, which necessarily take many years to complete, and space-for-time substitutions (Pickett, 1989). While the latter is faster, cross-location inferences often lead to erroneous or opposite interpretations due to site-specific effects (Pickett, 1989; Perret et al., 2024). We were interested in cropping system resilience to weather variation independently of soils. Therefore, we used a third approach, a “time-for-time substitution” of staggered planting dates within a single field. This enabled us to expose treatments to different heat and moisture stresses at critical growth stages as in multi-year studies (Fig. 1), but within a single year and without the uncertainties created by different soil conditions that multilocation studies create. Still, we caution that Planting B is not a best management practice for either oat or pea in the study region – Planting A is (Karki et al., 2022). As a result, in planting B, early growth stage temperatures were higher than would be expected and weed and arthropod communities would be different relative to crop phenology in Planting B (Ghersa and Holt., 1995; Way and Van Emden, 2000). Because of the urgency to develop stable, productive, and ecologically sound grain production systems, we found this tradeoff to be worthwhile.

5. Conclusion

Resistance to extreme weather and increasing demand for agricultural products continues to challenge current agricultural production systems. Our study suggests advantages of cereal-legume grain intercropping systems in the Western Corn Belt region to meet these challenges, as such systems may surpass monocultures in yields and resilience to both biotic and abiotic stressors. Integrating cereals and legumes (i.e., oats and peas) in our system maintains grain yield, improves quality, and enhances yield stability under varying weather conditions while managing weeds effectively. Despite significant variations in monoculture oats and pea yields under different planting dates and weather contexts, the intercropped oat-pea maintained a stable yield overall and demonstrated resilience against environmental stressors. This stability of intercropping system would likely be associated with the complementary growth patterns of oats and peas, which allowed one species to compensate for the other’s reduced performance even under adverse conditions. Additionally, our oat-pea intercrop produced grain that was of consistent quality and better suited for livestock feed than either monoculture. It also supported greater arthropod diversity and predatory arthropod activity, which can enhance pest controls and overall ecosystem health. While our study encountered challenges related to appropriate equipment and management practices, these can be overcome through collaboration with farmers, stakeholders, and policymakers to develop strategies for successfully implementing intercropping systems. Moreover, the yield-stabilizing effect of intercrops may be specific to environmental and management factors that require additional attention for making prudent decisions as a part of a production system. Intercropping offers a promising strategy for developing a land-use-efficient, productive, climate-resilient, and sustainable agricultural system.

CRediT authorship contribution statement

Shannon L. Osborne: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Dhurba Neupane:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Avery E. Knoll:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Data curation. **Karl A. Roeder:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patrick M. Ewing:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109773.

Data availability

Data and analyses are archived at the US Department of Agriculture Ag Data Commons: https://doi.org/10.15482/USDA.ADC/25843660

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