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Diversification with minor oilseeds: Effects on system productivity and nitrogen use efficiency in semi-arid Canadian prairies

Shayeb Shahariar[1] | **Mervin St. Luce**[1] | **Manjula Bandara**[2] | **Charles M. Geddes**[3] | **Kui Liu**[1] | **Prabhath Lokuruge**[4] | **Mohammad Khakbazan**[5] | **Brian McConkey**[6]

[1]Swift Current Research and Development Centre, Agriculture and Agri-Food Canada, Swift Current, Saskatchewan, Canada

[2]Alberta Agriculture and Irrigation, Crop Diversification Centre South, Brooks, Alberta, Canada

[3]Lethbridge Research and Development Centre, Agriculture and Agri-Food Canada, Lethbridge, Alberta, Canada

[4]Scott Research Farm, Agriculture and Agri-Food Canada, Scott, Saskatchewan, Canada

[5]Brandon Research and Development Centre, Agriculture and Agri-Food Canada, Brandon, Manitoba, Canada

[6]Viresco Solutions, Edmonton, Alberta, Canada

Correspondence
Mervin St. Luce, Swift Current Research and Development Centre, Agriculture and Agri-Food Canada, Swift Current, SK S9H 3×2, Canada.
Email: mervin.stluce@agr.gc.ca

Present address
Manjula Bandara, MCB Agric-Research Consulting, 106-204 17th Street E., Brooks, AB T1R 1R1, Canada.

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Abstract

Diversified cropping systems in the semi-arid Canadian prairies comprise major cereal, oilseed, and pulse crops. Further diversification with minor oilseeds, such as oriental (*Brassica juncea*), industrial (*Brassica carinata* L.), and yellow (*Sinapis alba* L.) mustard, camelina [*Camelina sativa* (L.) Crantz], and flax (*Linum usitatissimum* L.) could enhance productivity and sustainability. This 5-year (2018–2022) study, conducted at four sites (Brooks and Lethbridge, Alberta, and Scott and Swift Current, Saskatchewan), compared system productivity, expressed as annualized canola (*Brassica napus* L.) equivalent yield (CEY), and nitrogen use efficiency (NUE) of 14 cropping sequences, and examined the effect of stubbles, particularly minor oilseeds, on subsequent crop yields and the influence of soil and environmental driving factors. Averaged across sites, CEY was significantly higher for cropping sequences with minor oilseeds and pulses compared to continuous spring wheat (*Triticum aestivum* L.) or wheat with fallow. However, there were no significant differences in CEY among sequences with oilseeds and between sequences with oilseeds and field pea (*Pisum sativum* L.) versus lentil (*Lens culinaris* Medikus). While CEY and NUE were similar between sequences with minor oilseeds and canola, NUE (grain yield based) was significantly higher for the conventional (spring wheat, canola, and pulse)

Abbreviations: ANOVA, analysis of variance; BD, bulk density; CEY, canola equivalent yield; CF, chemical fallow; EC, electrical conductivity; extrac. P, extractable phosphorus; FP, field pea; IM, industrial mustard; LDA, linear discriminant analysis; LTA, long-term average; MANOVA, multivariate analysis of variance; NUE, nitrogen use efficiency; OM, oriental mustard; PC, principal component; PCA, principal component analysis; SOC, soil organic carbon; STN, soil total nitrogen; SWC, soil water content; YM, yellow mustard.

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than diversified sequence with minor oilseeds. Furthermore, the minor oilseeds had no adverse effect on subsequent pulse grain yields. Growing season and July mean air temperature most significantly impacted productivity and NUE. Our findings reveal that diversifying existing cropping systems with minor oilseeds can sustain productivity while enhancing NUE in the semi-arid Canadian prairies.

Plain Language Summary

A 5-year field study was conducted to evaluate the effect of including minor oilseed crops such as mustards, flax, and camelina into cropping sequences in the semi-arid Canadian prairies. No single cropping sequence consistently performed the best at all sites. Sequences with field peas or lentil plus oilseeds and spring wheat had higher production and nitrogen use efficiency than spring wheat monoculture and chemical fallow. Replacing canola with minor oilseeds did not affect productivity and nitrogen use efficiency. The mean air temperature during the growing season was the most critical factor affecting yield and nitrogen use efficiency, but others, such as mean air temperature in June, July, and August, as well as texture and soil water content before planting in spring, were also important. In conclusion, this study found that including minor oilseed crops can maintain productivity and help improve nitrogen use efficiency in the semi-arid Canadian prairies.

1 | INTRODUCTION

Cropping systems are expected to face major challenges due to climate change, which could adversely affect crop productivity and grain yield stability and thereby affect food security (Costa et al., 2024; Ghosh et al., 2023; Laforge et al., 2021; Lobell et al., 2011; Reza & Sabau, 2022; Rezaei et al., 2023). The predicted higher temperatures, changes in precipitation patterns, and more frequent extreme weather events (Chipanshi et al., 2021; Ghosh et al., 2023; Laforge et al., 2021; Ray et al., 2015; Rezaei et al., 2023) could directly affect agricultural production, crop growth cycles, yields, and quality; lead to shifts in pest and disease patterns and severity; and indirectly affect soil fertility (Xing & Wang, 2024; Yuan et al., 2024). Therefore, diversification of cropping systems is vital for improved crop productivity and yields while maintaining or increasing yield stability under varying climatic conditions (Costa et al., 2024; K. Liu, Johnson, et al., 2019; Martens et al., 2015; Sharma et al., 2021; Yang et al., 2024). However, rotational effects and site-specific agroclimatic conditions must be considered when designing diversified cropping systems (Colnenne-David & Doré, 2014).

Diversified cropping systems were shown to enhance resilience to extreme weather events (Gaudin et al., 2015), increase resource use efficiency (Zentner et al., 2011, 2004), stabilize crop yields (K. Liu, Johnson, et al., 2019), promote soil health (Iheshiulo et al., 2023), minimize pest incidence (Almdal & Costamagna, 2023; Krupinsky et al., 2002), improve water (Miller et al., 2003) and nitrogen use efficiency (NUE) (St. Luce et al., 2020), and increase profits and decrease economic risk (Archer et al., 2018; Khakbazan et al., 2022; 2025; Zentner et al., 2011) in the Canadian prairies. Despite these advantages, diversification of cropping systems in recent years has not increased. In the Canadian prairies, the area of tilled summer fallow decreased noticeably from 4,623,000 ha in 2001 to 518,000 ha in 2021, while the adoption of conservation tillage practices increased (Statistics Canada, 2024a). Nevertheless, there has been no substantial increase in diversity of cropping systems, with many crop rotations still comprising only two or three main crop species, such as spring wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), and lentil (*Lens culinaris* Medikus) (Iheshiulo et al., 2023; Martens et al., 2015; St. Luce et al., 2020). Furthermore, the 2018–2022 average seeded area (1000 ha) in the prairie provinces of Alberta, Manitoba, and Saskatchewan, were 8701, 6972, 1643, 1542, 363, 162, and 4 for canola, spring wheat, lentil, field pea (FP) (*Pisum sativum* L.), flax (*Linum usitatissimum* L.), mustards, and camelina [*Camelina sativa* (L.) Crantz], respectively (Statistics Canada, 2024b).

Oilseed crops are the core of prairie agriculture, with canola being the most widely grown in the Canadian prairies (Statistics Canada, 2024b). The expansion of canola acreage is expected to continue due to improved yields from new hybrid

cultivars and increasing global demand for edible oil and biofuel (Bueckert & Clarke, 2013). However, in the semi-arid Canadian prairies, drought and heat stresses during flowering often limit canola production (Gan et al., 2004; Miller et al., 2001). Therefore, it is crucial to diversify oilseed crops in the Canadian prairies to promote the sustainable development of oilseed-based cropping systems and achieve climate resiliency in the face of climate change.

Other Brassicaceae oilseed crops, such as mustards, are better adapted to drought and heat stress than canola (Wright et al., 1996), and they are generally considered as minor oilseed crops. Incorporating mustards into the cropping system can effectively help to control diseases, reduce canola admixtures, enhance yield stability, and improve soil moisture management. Studies on the Canadian prairies have shown that mustard species, such as oriental mustard (OM) (*Brassica juncea*) and yellow mustard (YM) (*Sinapis alba* L.), have higher drought tolerance than canola, especially during the flowering stage (Angadi et al., 2004, 2000; Blackshaw et al., 2011; Gan et al., 2004). Industrial mustard (IM) (*Brassica carinata* L.), as a green manure break crop, was shown to reduce pathogens and disease development substantially while enhancing the grain yield of the subsequent crop (Campanella et al., 2020). Besides Brassicaceae species like canola and mustards, camelina is a short-season minor oilseed crop suitable for rainfed environments across the North American Great Plains (Berti et al., 2016; Blackshaw et al., 2011; Gugel & Falk, 2006; Obour et al., 2018). Camelina and IM are well-known sources of biodiesel feedstock and can be grown as alternative oilseed crops on the Canadian prairies for the biodiesel industry (Blackshaw et al., 2011; Gugel & Falk, 2006). Camelina is highly valued for its drought and frost tolerance, pest and disease resistance, unique seed oil composition, high oil content, and satisfactory grain yields, particularly under low-input management and challenging environments (Zanetti et al., 2017). Obeng et al. (2024) reported that integrating camelina into wheat-based cropping systems in the Northern Great Plains had no impact on wheat yield but enhanced soil properties and overall cropping system productivity. Flax, a non-Brassicaceae oilseed crop, is grown in Canadian prairies for vegetable oil, high-protein meal, α-linolenic acid, dietary supplements, and biodiesel fuel (Benaragama et al., 2023). Flax production has stagnated due to lower yields and stability than canola, lower breeding success for increased yields compared to canola, as well as stubble management challenges, but it remains promising due to high gross returns from low input costs and moderate prices (Flax Council of Canada, 2019; May et al., 2010). Flax is a hardy, temperate plant that grows best in moist and warm climates with frost-free late spring conditions; however, heat stress during vegetative and flowering stages may decrease seed yield (Cui et al., 2022; Flax Council of Canada, 2019). Additionally, crop rotation and cultural practices influence flaxseed yield, nitrogen (N) content, NUE, and the N removal index (Sainju et al., 2020). Hence, the inclusion of these minor oilseed species in diversified cropping systems can help to further diversify the existing cropping systems in the Canadian prairies (Gugel & Falk, 2006), but more information on how they could affect subsequent crops and the cropping sequence is needed.

Core Ideas

- Cropping sequences with oilseeds and pulses had higher system productivity than continuous wheat or chemical fallow.
- System productivity and nitrogen use efficiency (NUE) were similar when minor oilseeds replaced canola in the cropping sequence.
- NUE was lower in diversified sequences with minor oilseeds than conventional with canola, wheat, and pulses.
- Growing season and July mean air temperature most significantly impacted productivity and NUE.
- Crop diversification with minor oilseed crops can sustain productivity and improve NUE.

Pulse crops are also important for diversifying cropping systems in the semi-arid Canadian prairies. In general, pulse crops, such as lentil and FP, require less water than cereal or oilseed crops, leaving critical residual soil water for the following crops (Gan et al., 2016; Niu et al., 2017). Additionally, the biological N fixation of pulse crops reduces the dependence on N fertilizer and increases the grain yields of the following crops, thus improving NUE, yield stability, and farm profitability (Khakbazan et al., 2022; K. Liu et al., 2020; Niu et al., 2017; St. Luce et al., 2015). Some Brassicaceae species can have allelopathic and antimicrobial effects through the production of glucosinolates and by-products, including thiocyanates and isothiocyanates (Nguyen et al., 2020). The concentration of glucosinolates varies by Brassicaceae species, with canola reported to have low concentrations compared to other Brassicaceae species and minor oilseed crops (Szmigielska et al., 2000). Moreover, it is not entirely clear whether minor oilseed crops could adversely affect growth and yield of subsequent pulse crops, which rely on biological N fixation, as well as the entire cropping sequence. Thus, this study aimed to integrate selected minor oilseed crops, such as camelina, IM, OM, YM, and flax, into cropping sequences that typically prioritize cereals (e.g., wheat), major oilseed crops (e.g., canola), and pulses such as lentil and FP in the semi-arid Canadian prairies. The specific objectives of this study were to (1) examine the impact of including selected minor oilseed crops on system productivity (canola equivalent yield [CEY]) and NUE based on

TABLE 1 Cropping sequences with major cereals, oilseeds, and pulses and diversified with minor oilseed crops used in the 5-year (2018–2022) cropping sequence study.

		Crop				
Treatment ID	**Cropping sequence**	**2018**	**2019**	**2020**	**2021**	**2022**
1	W-W-W-W-W	Spring wheat	Spring wheat	Spring wheat	Spring wheat	Spring wheat
2	W-W-CF-W-W	Spring wheat	Spring wheat	Chemical fallow	Spring wheat	Spring wheat
3	W-C-W-FP-W	Spring wheat	Canola	Spring wheat	Field pea	Spring wheat
4	W-C-W-L-W	Spring wheat	Canola	Spring wheat	Lentil	Spring wheat
5	W-IM-FP-W-YM	Spring wheat	Industrial mustard	Field pea	Spring wheat	Yellow mustard
6	W-C-FP-W-YM	Spring wheat	Canola	Field pea	Spring wheat	Yellow mustard
7	W-OM-FP-W-YM	Spring wheat	Oriental mustard	Field pea	Spring wheat	Yellow mustard
8	W-CM-FP-W-YM	Spring wheat	Camelina	Field pea	Spring wheat	Yellow mustard
9	W-F-FP-W-YM	Spring wheat	Flax	Field pea	Spring wheat	Yellow mustard
10	W-IM-L-W-YM	Spring wheat	Industrial mustard	Lentil	Spring wheat	Yellow mustard
11	W-C-L-W-YM	Spring wheat	Canola	Lentil	Spring wheat	Yellow mustard
12	W-OM-L-W-YM	Spring wheat	Oriental mustard	Lentil	Spring wheat	Yellow mustard
13	W-CM-L-W-YM	Spring wheat	Camelina	Lentil	Spring wheat	Yellow mustard
14	W-F-L-W-YM	Spring wheat	Flax	Lentil	Spring wheat	Yellow mustard

Note: This study was conducted at four sites (Brooks and Lethbridge in Alberta, and Scott and Swift Current in Saskatchewan, Canada). At Brooks, the lentil in the cropping sequence 4 W-C-W-L-W was replaced by chemical fallow, as the lentil crop died at an early growth stage due to root rot in the 2021 cropping season.
Abbreviations: C, canola; CF, chemical fallow; CM, camelina; F, flax; FP, field pea; IM, industrial mustard; L, lentil; OM, oriental mustard; W, spring wheat; YM, yellow mustard.

CEY and actual grain yield; (2) examine the impact of stubble, on grain yield and NUE of subsequent crops, particularly these selected minor oilseed crops on subsequent FP and lentil crops, and spring wheat following the pulse crops; and (3) assess the soil and environmental factors that affect system productivity in the semi-arid Canadian prairies.

2 | MATERIALS AND METHODS

2.1 | Field site description and experimental design

The field study was conducted during five consecutive cropping years (2018–2022) at four sites in the semi-arid Canadian prairies: Brooks (50˚33′ N, 111˚53′ W) and Lethbridge (49˚69′ N, 112˚70′ W) in Alberta; Scott (52˚21′ N, 108˚50′ W) and Swift Current (50˚25′ N, 107˚44′ W) in Saskatchewan (Table 1). The soils at the Brooks and Swift Current sites were Brown Chernozems (Aridic Haploboroll) (Soil Classification Working Group, 1998; Soil Survey Staff, 2022) with loam and silt loam textures, respectively, and Dark Brown Chernozems (Typic Haploboroll) (Soil Classification Working Group, 1998; Soil Survey Staff, 2022) at Lethbridge and Scott with loam textures (Table 2). A summary of the site characteristics at the initiation of the study is presented in Table 2, and further details were reported in Khakbazan et al. (2025).

This study included 14 cropping sequence treatments arranged in a randomized complete block design (Table 1) with four replicates at each site. The plot sizes varied among sites based on the availability of seeding equipment and were 3 m × 12 m at Brooks, 4.24 m × 12 m at Lethbridge, 3.65 m × 10 m at Scott, and 4.0 m × 10 m at Swift Current. Row spacing at Brooks, Lethbridge, Scott, and Swift Current was 22.5, 30.5, 22.9, and 25.0 cm, respectively. Cropping sequence 1 (W-W-W-W-W) was continuous spring wheat (W; cv. AAC Brandon), while cropping sequence 2 (W-W-CF-W-W) had a chemical fallow (CF) in the third year (2020). Cropping sequences 3 (W-C-W-FP-W) and 4 (W-C-W-L-W) were conventional diversified cropping sequences in the Canadian prairies and involved spring wheat, canola (C; cv. L233P), and a pulse crop (lentil [L; cv. CDC Maxim] or FP [cv. CDC Meadow]), with only the type of pulse crop differing between them. Due to the lentil crop failure as a result of severe Aphanomyces root rot at the Brooks site in 2021, the lentil phase in W-C-W-L-W at Brooks was replaced by CF. Cropping sequences 5–14 involved oilseed crops (canola, IM [cv. A120], OM [cv. AC Cutlass], camelina [CM; cv. Cypress], flax [F; cv. CDC Glas], and YM [cv. Andante]) rotated with cereal (spring wheat) and pulse (lentil or FP) crops. In all cases, the minor oilseed crops and canola were grown in the second year, followed by either FP (cropping sequences 5 [W-IM-FP-W-YM], 6 [W-C-FP-W-YM], 7 [W-OM-FP-W-YM], 8 [W-CM-FP-W-YM], 9 [W-F-FP-W-YM]) or lentil (cropping sequences 10 [W-IM-L-W-YM], 11 [W-C-

TABLE 2 Soil physical and chemical properties at Brooks, Lethbridge, Scott, and Swift Current in Fall 2018.

Site	Depth (cm)	Sand (%)	Clay (%)	Texture	Soil classification	pH	EC ($\mu S\ cm^{-1}$)	SOC ($g\ kg^{-1}$)	STN ($g\ kg^{-1}$)	Mineral N ($kg\ ha^{-1}$)	Extrac. P ($kg\ ha^{-1}$)
Brooks, AB	0–15	33.5	25.3	Loam	Brown Chernozem	8.00	570	12.7	1.28	19.1	92.2
	15–30							10.7	1.08	19.1	67.6
	30–60							7.6	0.73	45.8	44.6
	0–60							10.3	1.00	84.0	201.4
Lethbridge, AB	0–15	43.0	23.8	Loam	Dark Brown Chernozem	8.20	210	16.0	1.80	21.1	21.3
	15–30							11.4	1.30	14.9	6.9
	30–60							8.4	0.88	25.3	9.5
	0–60							11.9	1.30	61.3	37.7
Scott, SK	0–15	36.0	20.0	Loam	Dark Brown Chernozem	6.50	260	5.0	0.53	8.5	16.7
	15–30							2.5	0.28	5.3	1.7
	30–60							2.1	0.20	8.6	2.7
	0–60							3.2	0.30	22.4	27.7
Swift Current, SK	0–15	29.8	21.8	Silt loam	Brown Chernozem	6.23	340	13.8	1.40	32.1	41.3
	15–30							8.1	0.95	21.9	14.4
	30–60							5.9	0.63	32.8	20.1
	0–60							9.3	1.00	86.8	76.2

Note: Mineral N is the sum of nitrate-nitrogen and ammonium-nitrogen contents. Mineral N and extractable P at 0–60 cm were the sum of all depths, while for SOC and TKN, it was the average of all depths.

Abbreviations: AB, Alberta; EC, electrical conductivity; Extrac. P, extractable soil phosphorous; N, nitrogen; SK, Saskatchewan; SOC, soil organic carbon; STN, soil total nitrogen.

L-W-YM], 12 [W-OM-L-W-YM], 13 [W-CM-L-W-YM], 14 [W-F-L-W-YM]) to examine their impacts on pulses. YM was grown in the final cropping year across sequences 5–14.

2.2 | Crop and soil fertility management

Seeding was carried out in May under suboptimal soil moisture conditions (dry) for crop emergence and establishment in most years and at all sites. Crop-specific target seeding densities are provided in Table S1. The target seeding density (number of seed m^{-2}) was 300–325 for spring wheat, 150 for YM, IM, OM, and canola, 75–100 for FP, 132–150 for lentil, 650 for flax, and 500 for camelina. Supplemental irrigation was provided from May to July at Brooks and Lethbridge to enhance crop emergence but was discontinued once the crops emerged. Total supplemental irrigation at Brooks was 0, 0, 29, 34.5, and 24 mm in 2018, 2019, 2020, 2021, and 2022, respectively, and 25.4, 25.4, 50.8, 25.4, and 25.4 mm in 2018, 2019, 2020, 2021, and 2022, respectively, at Lethbridge.

Nitrogen and phosphorus (P) application rates are provided in Table 3. Urea (46-0-0) was used as the main N source, while monoammonium phosphate (11-52-0) and triple superphosphate (0-46-0) were used as P sources (20-24 kg P_2O_5 ha^{-1}), depending on the site and year. The N applications were either mid-row banded or side-banded at seeding, while P was applied with the seed. All crops were fertilized at seeding to produce regional-average yields in 2018–2020. Pulses in 2020 received ≈5 kg N ha^{-1} at Brooks and Scott through the application of ammonium phosphate. Fertilizer N requirements in 2021 and 2022 were based on the fall soil mineral N concentration at 0- to 60-cm soil depth and target yields (Saskatchewan Agriculture, 2018–2022) according to the soil zones and accounted for estimated pulse N credits by multiplying the previous FP and lentil grain yields by 0.005 and 0.004, respectively (Miller et al., 2002). Total available soil N was determined as the sum of the estimated pulse N credit and the fall soil mineral N at the 0- to 60-cm soil depth. Total N requirements were 90 and 104 kg N ha^{-1} for spring wheat and 77 and 96 kg N ha^{-1} for all other non-pulse crops grown in year 4 for the Brown and Dark Brown soil zones, respectively.

Glyphosate (Roundup WeatherMAX, Bayer CropScience Inc.; 900 g ai ha^{-1}) was applied as a pre-seed burn-off across most plots at all sites. The herbicide Trifluralin (Bonanza 10G, Loveland Products Canada Inc.; 850 g ai ha^{-1}) was also applied to the soil surface in some plots during the fall of 2018 and 2020 years of the study. Post-emergent herbicides were applied at the recommended rates and at the appropriate growth stages to control broadleaf and grassy weeds for each crop. Fungicides and insecticides were applied as needed, based on local recommendations for each crop and year. The weed counts data were not statistically analyzed because the experiment was not specifically designed to examine weed dynamics. However, summaries are provided for

TABLE 3 Nitrogen (N) and phosphorus (P) rates applied over the study period (2018–2022) at Brooks, Lethbridge, Scott, and Swift Current.

			N (kg N ha^{-1})						P (kg P_2O_5 ha^{-1})					
Site	Treatment ID	Cropping sequence	2018	2019	2020	2021	2022	Mean (2018–2022)	2018	2019	2020	2021	2022	Mean (2018–2022)
Brooks, AB	1	W-W-W-W-W	55	55	55	19	7	38.2	20	22	22	20	20	20.8
	2	W-W-CF-W-W	55	55	0	55	7	34.4	20	22	0	20	20	16.4
	3	W-C-W-FP-W	55	55	55	0	7	34.4	20	22	22	20	20	20.8
	4	W-C-W-L-W	55	55	55	0	7	34.4	20	22	22	20	20	20.8
	5	W-IM-FP-W-YM	55	55	5	19	7	28.2	20	22	22	20	20	20.8
	6	W-C-FP-W-YM	55	55	5	19	7	28.2	20	22	22	20	20	20.8
	7	W-OM-FP-W-YM	55	55	5	7	7	25.8	20	22	22	20	20	20.8
	8	W-CM-FP-W-YM	55	55	5	7	7	25.8	20	22	22	20	20	20.8
	9	W-F-FP-W-YM	55	55	5	28	7	30.0	20	22	22	20	20	20.8
	10	W-IM-L-W-YM	55	55	5	19	7	28.2	20	22	22	20	20	20.8
	11	W-C-L-W-YM	55	55	5	14	7	27.2	20	22	22	20	20	20.8
	12	W-OM-L-W-YM	55	55	5	35	7	31.4	20	22	22	20	20	20.8
	13	W-CM-L-W-YM	55	55	5	19	7	28.2	20	22	22	20	20	20.8
	14	W-F-L-W-YM	55	55	5	14	7	27.2	20	22	22	20	20	20.8
Lethbridge, AB	1	W-W-W-W-W	85	55	50	67	66	64.6	22	22	20	20	20	20.8
	2	W-W-CF-W-W	85	55	0	28	34	40.4	22	22	0	20	20	16.8
	3	W-C-W-FP-W	85	55	50	0	53	48.6	22	22	20	20	20	20.8
	4	W-C-W-L-W	85	55	50	0	53	48.6	22	22	20	20	20	20.8
	5	W-IM-FP-W-YM	85	55	0	40	34	42.8	22	22	20	20	20	20.8
	6	W-C-FP-W-YM	85	55	0	40	34	42.8	22	22	20	20	20	20.8
	7	W-OM-FP-W-YM	85	55	0	40	44	44.8	22	22	20	20	20	20.8
	8	W-CM-FP-W-YM	85	55	0	40	51	46.2	22	22	20	20	20	20.8
	9	W-F-FP-W-YM	85	55	0	40	51	46.2	22	22	20	20	20	20.8
	10	W-IM-L-W-YM	85	55	0	62	21	44.6	22	22	20	20	20	20.8
	11	W-C-L-W-YM	85	55	0	62	21	44.6	22	22	20	20	20	20.8
	12	W-OM-L-W-YM	85	55	0	62	8	42.0	22	22	20	20	20	20.8
	13	W-CM-L-W-YM	85	55	0	62	21	44.6	22	22	20	20	20	20.8
	14	W-F-L-W-YM	85	55	0	62	34	47.2	22	22	20	20	20	20.8

(Continues)

TABLE 3 (Continued)

Site	Treatment ID	Cropping sequence	N (kg N ha^{-1})						P (kg P_2O_5 ha^{-1})					
			2018	2019	2020	2021	2022	Mean (2018–2022)	2018	2019	2020	2021	2022	Mean (2018–2022)
Scott, SK	1	W-W-W-W-W	63	55	55	8	75	51.2	24	22	22	20	20	21.6
	2	W-W-CF-W-W	63	55	0	8	75	40.2	24	22	0	20	20	17.2
	3	W-C-W-FP-W	63	55	55	0	75	49.6	24	22	22	20	20	21.6
	4	W-C-W-L-W	63	55	55	0	75	49.6	24	22	22	20	20	21.6
	5	W-IM-FP-W-YM	63	55	5	8	59	38.0	24	22	22	20	20	21.6
	6	W-C-FP-W-YM	63	55	5	8	59	38.0	24	22	22	20	20	21.6
	7	W-OM-FP-W-YM	63	55	5	8	59	38.0	24	22	22	20	20	21.6
	8	W-CM-FP-W-YM	63	55	5	8	52	36.6	24	22	22	20	20	21.6
	9	W-F-FP-W-YM	63	55	5	8	59	38.0	24	22	22	20	20	21.6
	10	W-IM-L-W-YM	63	55	5	8	52	36.6	24	22	22	20	20	21.6
	11	W-C-L-W-YM	63	55	5	8	59	38.0	24	22	22	20	20	21.6
	12	W-OM-L-W-YM	63	55	5	8	52	36.6	24	22	22	20	20	21.6
	13	W-CM-L-W-YM	63	55	5	8	52	36.6	24	22	22	20	20	21.6
	14	W-F-L-W-YM	63	55	5	8	52	36.6	24	22	22	20	20	21.6
Swift Current, SK	1	W-W-W-W-W	80	55	50	56	76	63.4	0	22	20	20	20	16.4
	2	W-W-CF-W-W	80	55	0	31	67	46.6	0	22	0	20	20	12.4
	3	W-C-W-FP-W	80	55	50	0	76	52.2	0	22	20	20	20	16.4
	4	W-C-W-L-W	80	55	50	0	76	52.2	0	22	20	20	20	16.4
	5	W-IM-FP-W-YM	80	55	0	31	58	44.8	0	22	20	20	20	16.4
	6	W-C-FP-W-YM	80	55	0	31	58	44.8	0	22	20	20	20	16.4
	7	W-OM-FP-W-YM	80	55	0	31	58	44.8	0	22	20	20	20	16.4
	8	W-CM-FP-W-YM	80	55	0	31	58	44.8	0	22	20	20	20	16.4
	9	W-F-FP-W-YM	80	55	0	31	58	44.8	0	22	20	20	20	16.4
	10	W-IM-L-W-YM	80	55	0	42	58	47.0	0	22	20	20	20	16.4
	11	W-C-L-W-YM	80	55	0	42	58	47.0	0	22	20	20	20	16.4
	12	W-OM-L-W-YM	80	55	0	42	58	47.0	0	22	20	20	20	16.4
	13	W-CM-L-W-YM	80	55	0	42	35	42.4	0	22	20	20	20	16.4
	14	W-F-L-W-YM	80	55	0	49	43	45.4	0	22	20	20	20	16.4

Abbreviations: AB, Alberta; C, canola; CF, chemical fallow; CM, camelina; F, flax; FP, field pea; IM, industrial mustard; L, lentil; OM, oriental mustard; SK, Saskatchewan; W, spring wheat; YM, yellow mustard.

information (Table S2). Broadleaf weeds were the dominant weed species. The most common weeds were Kochia, Shepherd's Purse, Flixweed, Volunteer Wheat, and Dandelion at Brooks; Kochia, Volunteer Wheat, and Wild Oat at Swift Current; and Prickly Lettuce, Green Foxtail, Dandelion, Wild buckwheat, Kochia, Green Foxtail, Stork's Bill, and Lamb's Quarters at Lethbridge (data not shown and was not recorded at Scott).

2.3 | Agronomic measurements

Crop emergence and post-harvest plant density were measured approximately 2–3 weeks after seeding and immediately after harvest. This was done by counting the average number of plants in two separate 1-m row lengths at the front and back of each plot. Plant height was measured at 50% flowering and maturity using six randomly chosen plants from the middle rows of each plot, but the results are not reported here. Weed counts involved recording the total grassy and broadleaf weeds from two 0.5 m^2 areas in each plot (front and back) in June before applying post-emergence herbicides. The five most common weed species in the entire trial area were also recorded. These areas were also marked for subsequent weed biomass collection, which was done in late July to early August by harvesting weeds from the marked 0.5 m^2 areas before seed shattering and crop maturity. The weed biomass was dried and weighed to determine total dry matter.

2.4 | Grain and CEYs

Grain yield was determined by harvesting each plot with a small plot combine. The straw was returned to the same plots after chopping through the combine or with a mower. Ten plants from the middle row of each plot were randomly selected, their roots cut off, and the dry weights of the aboveground biomass were measured. Yield components were also assessed using the 10 randomly chosen plants per plot. The harvested grain was cleaned, dried, weighed, and adjusted for moisture (14.5% for spring wheat, 10% for canola and flax, 16% for FP, 14% for lentil, 8.5% for camelina, and 9.5% for mustards). The grain yield was reported in kg ha^{-1}. Other yield components such as the number of heads or pods per plant and seeds per plant were recorded but are not reported here. For comparison at the cropping sequence level, the grain yields of the individual crops were converted to CEY. Canola was selected as the reference crop because it is the most widely grown major oilseed in the North American Great Plains, including the Canadian prairies (K. Liu, Johnson, et al., 2019). A 5-year (2018–2022) average of individual crop prices (Table S3) reported by Saskatchewan Agriculture (2018–2022) was used to calculate the CEY for the grain yield harvested from each experimental plot during the study period. However, the crop price for IM was not included, so the YM price was used as a substitute. The 5-year averages ($\$$ kg^{-1}) were 0.268, 0.546, 0.498, 0.293, 1.014, 0.816, 0.551, 0.578, and 1.014 for W, C, L, FP, IM, OM, CM, F, and YM, respectively. The CEY was calculated as:

$$\text{CEY} = \frac{\text{Price}_{\text{non-canola}}}{\text{Price}_{\text{canola}}} \times \textit{Yield}_{\text{non-canola}} \quad (1)$$

where CEY is the canola equivalent yield, $\text{Price}_{\text{non-canola}}$ is the grain price of non-canola crops, $\text{Price}_{\text{canola}}$ is the grain price of canola, and $\text{Yield}_{\text{non-canola}}$ is the grain yield of non-canola crops. For each cropping sequence, the annualized CEY was used to represent the system production.

2.5 | NUE for grain and CEYs

The NUE was estimated based on CEY (NUE_{CEY}) and grain yield ($\text{NUE}_{\text{Grain}}$). The NUE was calculated on a plot basis as:

$$\text{NUE}_{\text{CEY, grain}} = \frac{\text{Yield}_{\text{CEY, grain}}}{\text{Fertilizer N} + \textit{Soil} \text{ mineral N}} \quad (2)$$

where $\text{NUE}_{\text{CEY,grain}}$ are the CEY and grain yield based NUE (kg^{-1} kg^{-1}), respectively, $\text{Yield}_{\text{CEY,grain}}$ is the CEY and grain yield (kg ha^{-1}), respectively, Fertilizer N (kg N ha^{-1}) is the amount of fertilizer N applied, and Soil mineral N (kg N ha^{-1}) is the soil mineral N (NH_4^+–N and NO_3^-–N) content at the 0- to 60-cm depth measured the previous fall. The NUE at the cropping sequence level was the average NUE of all crops within the cropping sequence.

2.6 | Soil sampling and laboratory analysis

Composite soil samples (two to three soil cores per plot) were collected at the 0- to 15-cm, 15- to 30-cm and 30- to 60-cm depths in spring and after harvest in the fall of each year from 2018 to 2022. Laboratory analyses for years 1–3 were performed by IEH Services Canada, while years 4 and 5 were conducted by CARA Soil Health Lab using the same laboratory procedures. Gravimetric soil moisture content was measured from a 20-g subsample that was oven-dried at 105°C for 24 h. The remaining portion was air-dried and sieved at 2 mm. Soil bulk density (BD, g cm^{-3}) was calculated after determining the gravimetric moisture content from the composite samples based on the volume of the soil core samples collected in the fall after harvest (Carter & Gregorich, 2007). The soil water content (SWC; mm) was calculated from gravimetric water content multiplied by the corresponding BD. Soil texture was determined according to the hydrometer method (Carter & Gregorich, 2007). Soil pH and

electrical conductivity were measured using a 1:2 soil:water ratio. Nitrate-nitrogen (NO_3^-–N) and ammonium-N (NH_4^-–N) were measured colorimetrically after extraction with 2 M KCl as described by Maynard et al. (2008). Soil mineral N was taken as the sum of NO_3–N and NH_4–N. Soil extractable P (extrac. P) was determined using the modified Kelowna extraction procedure (Qian et al., 1994). Briefly 2.5 g air-dried soil was mixed with 25 mL of modified Kelowna extract (0.015 M NH_4F, 0.5 M HOAc, 1 M NH_4OAc), shaken for 30 min and filtered, and the P concentration was measured colorimetrically following the Molybdenum Blue method. Soil total N (STN) was determined after Kjeldahl digestion (Rutherford et al., 2008). Soil organic carbon (SOC) was determined following the Walkley–Black method described by Skjemstad and Baldock (2008). The soil mineral N and extrac. P (kg ha^{-1}) were calculated by multiplying their concentrations by the respective BD and layer thickness. Total soil mineral N at 0–60 cm was calculated by adding mineral N from all individual depths.

2.7 | Growing season conditions

Meteorological data, including the precipitation and air temperatures in each growing season, were collected on-site or from a nearby weather station affiliated with Environment and Climate Change Canada. The growing season (May to August) and the long-term average (LTA; 1981–2010) precipitation and air temperature for all sites are presented in Table 4. Depending on the year and month, precipitation during the growing season varied among sites. The average growing season mean air temperature variation was within 0°C–1.9°C above and below the LTA at all sites (Table 4). The 2018 and 2021 growing seasons were the driest at all sites, with mild to severe drought conditions experienced at all sites (Table 4). The total growing season precipitation in 2018 was 76%, 59%, 64%, and 83% lower compared to the LTA at Brooks, Lethbridge, Scott, and Swift Current, respectively. Growing season precipitation was highest in 2022 at Brooks, in 2020 at Lethbridge and Scott, and in 2019 at Swift Current. The growing season precipitation in 2022 was 7% higher at Brooks, 0.2% lower at Lethbridge, 15% lower at Scott, and 22% lower at Swift Current compared to the LTA.

2.8 | Statistical analysis

The statistical analyses were performed using R (version 4.3.2) (R Core Team, 2023). The normality of the residuals was assessed using the Shapiro–Wilk test and histogram, and the homogeneity of variances was checked using Levene's test in the "car" package. Data visualization was done with a bar plot with mean and standard error using "ggplot2." Analysis of variance (ANOVA) was performed using the linear mixed models in package "lme4" separately for each site and across all sites to determine the effect of cropping sequences on CEY, NUE_{CEY}, and NUE_{Grain}. In the statistical model for each site, the cropping sequence was considered as a fixed factor with fixed effect, and the year and replicate were considered as random factors with random effects. Across sites, the cropping sequence was considered as the fixed factor, and site and year were random factors. Significant effects were declared at $p < 0.05$, and treatment means were compared with post hoc pairwise comparison using the Tukey method in package "agricolae" and visualized using "multcomp" and "multcompView." An ANOVA with the linear model was also performed to determine the impact of previous stubble (from the oilseed crops phase) on subsequent grain yields and NUE_{Grain} for each site and across sites. Here, the stubbles were considered the fixed effect for individual sites and across sites. Pre-planned contrast analysis was performed to compare cropping sequence productivity and NUE between pre-specified cropping sequence groups: continuous wheat versus sequences with FP and oilseed crops; continuous wheat versus sequences with lentil and oilseed crops; sequences with canola versus minor oilseed crops that replaced canola in the sequence; conventional diversified sequences with canola, spring wheat, and pulses versus diversification with minor oilseed crops and pulses; and sequences with FP and minor oilseed crops versus lentil and minor oilseed crops.

Several soil and environmental parameters were used as factors that may affect grain yield and CEY. Principal component analysis (PCA) was performed to assess the importance of the soil and environmental variables as driving factors and identify correlated variables using the "vegan" and "MASS" packages. A preliminary PCA analysis showed that SOC and STN were highly correlated and that BD had little to no impact; hence, these variables were removed to avoid multicollinearity and overfitting issues. We included sand percentage, clay percentage, and extrac. P, SOC, and SWC in spring and fall, mineral N in spring and fall, monthly average air temperatures from May to August, monthly total precipitation from May to August, average growing season (May to August) air temperature, and total growing season (May to August) precipitation into the PCA for this study. The PCA biplots were visualized using the "FactoMineR" and "factoextra" packages for the sites, years, crops, and cropping sequences as factors to uncover underlying patterns. The contribution (expressed as %) of each response variable to the principal component (PC) 1 and 2 was also visualized using the same R packages. The correlation of CEY, grain yield, NUE_{CEY}, NUE_{Grain}, soil, and environmental variables with each dimension, that is, PC, was visualized using "corrplot." Multivariate analysis of variance (MANOVA) was performed using the "vegan" package to determine if there were significant differences in CEY, grain yield, NUE_{CEY},

TABLE 4 Growing season (May to August) precipitation and mean air temperature during the study period at Brooks, Lethbridge, Scott, and Swift Current.

		Brooks, AB		Lethbridge, AB		Scott, SK		Swift Current, SK	
Year	Month	Precipitation (mm)	Mean air temperature (˚C)	Precipitation (mm)	Mean air temperature (˚C)	Precipitation (mm)	Mean air temperature (˚C)	Precipitation (mm)	Mean air temperature (˚C)
2018	May	12.3	14.6	20.2	15.2	29.6	13.6	25.6	14.6
	Jun	45.8	16.7	58.4	16.6	29.6	16.2	16.9	17.1
	Jul	30.8	19.1	33.0	19.1	48.2	17.5	51.2	18.8
	Aug	16.5	17.7	18.3	18.7	24.6	16.0	31.0	18.7
	May–Aug	105.4	17.0	129.9	17.4	132.0	15.8	124.7	17.3
2019	May	7.2	10.1	55.4	10.7	12.7	9.1	13.3	9.5
	Jun	26.4	16.1	18.0	16.2	97.7	15.0	156.0	15.8
	Jul	46.6	18.2	44.0	18.7	107.8	16.1	11.1	17.7
	Aug	26.0	17.3	27.7	18.2	18.0	14.4	42.6	16.8
	May–Aug	106.2	15.4	145.1	16.0	236.2	13.6	223.0	14.9
2020	May	30.2	10.8	66.3	11.7	51.9	9.9	37.1	10.7
	Jun	52.7	15.5	109.4	16.1	72.5	14.6	68.9	15.3
	Jul	36.4	18.5	24.8	18.3	123.0	17.2	56.9	17.7
	Aug	9.3	19.4	14.5	19.4	27.0	16.3	11.2	19.2
	May–Aug	128.6	16.1	215.0	16.4	274.4	14.5	174.1	15.7
2021	May	50.2	9.8	34.3	10.4	44.3	9.4	35.9	9.5
	Jun	12.8	18.4	14.0	18.7	43.8	17.3	29.6	18.4
	Jul	12.4	21.3	4.0	21.9	10.4	19.6	38.9	21.7
	Aug	31.0	18.0	37.5	18.7	51.3	17.2	55.8	18.1
	May–Aug	106.4	16.9	89.8	17.4	149.8	15.9	160.2	16.9
2022	May	6.9	11.0	5.5	11.3	11.0	10.0	51.2	10.9
	Jun	81.6	16.0	103.5	15.2	57.1	15.0	37.7	15.9
	Jul	89.4	19.8	63.9	19.9	86.5	18.3	90.4	19.8
	Aug	20.8	20.6	33.0	21.4	32.6	18.6	7.5	20.9
	May–Aug	198.7	16.9	205.9	16.9	187.2	15.5	186.8	16.9
1981–2010	May	41.0	11.3	49.5	11.1	36.3	10.8	50.5	10.8
	Jun	64.5	15.6	76.8	15.3	61.8	15.3	77.7	15.4
	Jul	44.9	18.5	39.4	18.2	72.1	17.1	54.0	18.4
	Aug	35.3	17.7	40.6	17.5	45.7	16.5	45.6	18.1
	May–Aug	185.7	15.8	206.3	15.5	215.9	14.9	227.8	15.7

Abbreviations: AB, Alberta; SK, Saskatchewan.

NUE_{Grain}, soil, and environmental variables across independent variables, such as site, year, crop, and cropping sequence. Linear discriminant analysis (LDA) was performed as a post hoc test for MANOVA to separate based on categories, that is, sites, years, crops, and cropping sequences from each other using the package "MASS" and visualized using "ggplot2." Data were subject to square root transformation to meet the assumption of normality and homogeneity of variance for MANOVA, LDA, and PCA. For the multivariate analysis, we primarily used soil data collected from Spring of 2019 to Spring of 2022 as initial soil samples were not collected in Spring of 2018 but in Fall of 2018. To ensure consistency, the 2018 data for CEY, grain yield, NUE_{CEY}, and NUE_{Grain} were excluded so that all the plots would have uniformity in the soil data throughout the study.

3 | RESULTS

3.1 | Cropping sequence productivity

The cropping sequences differed significantly ($p < 0.001$) in CEY across sites and at individual sites (Table 5). However, no single cropping sequence performed the best

TABLE 5 Analysis of variance (ANOVA Type III) showing the effects of cropping sequence on canola equivalent yield, canola equivalent and grain yield based nitrogen use efficiency within and across sites in the Canadian prairies.

		CEY		NUE_{CEY}		NUE_{Grain}	
	Effects/sources of variation	***F* value**	***p* value**	***F* value**	***p* value**	***F* value**	***p* value**
Brooks, AB	Cropping sequence	8.1152	<0.001***	2.2909	0.0071**	1.1700	0.3021^{ns}
Lethbridge, AB	Cropping sequence	6.3660	<0.001***	5.1765	<0.001***	3.3010	<0.001***
Scott, SK	Cropping sequence	6.4926	<0.001***	4.8756	<0.001***	3.4046	<0.001***
Swift Current, SK	Cropping sequence	4.1746	<0.001***	2.7166	0.0013**	2.3220	0.0063**
Across sites	Cropping sequence	6.0255	<0.001***	3.2496	<0.001***	2.0980	0.0121*

Abbreviations: AB, Alberta; CEY, canola equivalent yield; NUE, nitrogen use efficiency; SK, Saskatchewan.
*, **, and *** denote significance at the 0.05, 0.01, and 0.001 probability levels, respectively. ^{ns}represents not significant at the 0.05 probability level.

across all sites, nor did one stand out at any specific site. Hence, the performance of the cropping sequences was site-specific (Figure 1A). The W-W-CF-W-W sequence consistently showed significantly ($p < 0.001$) lower CEY at all sites compared to other cropping sequences, except W-W-W-W-W (Figure 1A). Across sites, the CEY was significantly ($p < 0.001$) lower for W-W-W-W-W and W-W-CF-W-W compared to most other cropping sequences, and CEY did not differ among the other sequences (Table 5; Figure 1A).

At Brooks, the W-OM-L-W-YM sequence was the most productive, showing 69.4% and 86.8% higher CEY than the W-W-W-W-W and W-W-CF-W-W sequences, respectively (Figure 1A). At Lethbridge, the W-C-FP-W-YM sequence was the most productive and had 45.4% and 67.8% higher CEY than the W-W-W-W-W and W-W-CF-W-W sequences, respectively (Figure 1A). At Scott, the W-IM-FP-W-YM sequence had 74.4% and 116.7% higher CEY than the W-W-W-W-W and W-W-CF-W-W sequences, respectively, while at Swift Current, the W-IM-L-W-YM sequence produced 37.7% and 73.1% higher CEY than the W-W-W-W-W and W-W-CF-W-W sequences, respectively (Figure 1A). The conventional diversified sequence (W-C-W-FP-W and W-C-W-L-W) had, on average, 23.4% and 49.7% higher CEY than W-W-W-W-W and W-W-CF-W-W, respectively, across sites (Figure 1A). Averaged across sites, W-IM-FP-W-YM had 40.6% and 70.5% higher CEY than the W-W-W-W-W and W-W-CF-W-W sequences, respectively (Figure 1A).

The contrast analysis across sites revealed that cropping sequences with oilseed crops and FP (W-IM-FP-W-YM, W-C-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, and W-F-FP-W-YM) or lentil (W-IM-L-W-YM, W-C-L-W-YM, W-OM-L-W-YM, W-CM-L-W-YM, and W-F-L-W-YM) had significantly ($p < 0.001$) higher CEY compared to W-W-W-W-W (Table 6). However, CEY was statistically comparable between conventional diversified sequences with spring wheat, canola, and pulses (W-C-W-FP-W and W-C-W-L-W) and diversification with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, W-F-FP-W-YM, W-IM-L-W-YM, W-OM-L-W-YM, W-CM-L-W-YM, and W-F-L-W-YM), and between sequences with minor oilseed crops and FP (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, and W-F-FP-W-YM) versus lentil (W-IM-L-W-YM, W-OM-L-W-YM, W-CM-L-W-YM, and W-F-L-W-YM). Moreover, there were no significant differences ($p > 0.05$) between sequences with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, W-IM-L-W-YM, W-OM-L-W-YM, and W-CM-L-W-YM) and those with canola (W-C-FP-W-YM and W-C-L-W-YM) (Table 6).

3.2 | NUE of cropping sequences

The cropping sequence had a significant effect ($p < 0.05$) on NUE_{CEY} and NUE_{Grain} at all sites and across sites, except for Brooks, where the effect was not significant ($p > 0.05$) for NUE_{Grain} (Table 5). The NUE_{CEY} and NUE_{Grain} were highest at Brooks for W-F-FP-W-YM (2.93 kg kg^{-1}) and W-F-FP-W-YM (4.44 kg kg^{-1}), at Lethbridge for W-C-FP-W-YM (5.03 kg kg^{-1}) and W-C-FP-W-YM (7.66 kg kg^{-1}), at Scott for W-F-L-W-YM (3.78 kg kg^{-1}) and W-C-W-L-W (5.44 kg kg^{-1}), and at Swift Current for W-IM-FP-W-YM (4.76 kg kg^{-1}) and W-W-W-W-W (6.66 kg kg^{-1}), respectively. The NUE_{CEY} and NUE_{Grain} were lowest at Brooks for W-C-W-L-W (1.34 kg kg^{-1}) and W-C-W-L-W (2.24 kg kg^{-1}), at Lethbridge for W-W-CF-W-W (2.08 kg kg^{-1}) and W-W-CF-W-W (4.23 kg kg^{-1}), at Scott for W-W-CF-W-W (1.45 kg kg^{-1}) and W-W-CF-W-W (2.96 kg kg^{-1}), and at Swift Current for W-W-CF-W-W (2.30 kg kg^{-1}) and W-OM-L-W-YM (3.68 kg kg^{-1}), respectively. For both NUE_{CEY} and NUE_{Grain}, no single cropping sequence performed the best at all sites; therefore, the performance of the individual sequences on NUE was site-specific (Figure 1B,C). Across sites, the highest NUE_{CEY} (3.71 kg kg^{-1}) and NUE_{Grain} (5.39 kg kg^{-1}) were observed for W-OM-L-W-YM and W-F-FP-W-YM, respectively, and the lowest NUE_{CEY} (1.80 kg kg^{-1}) and NUE_{Grain} (3.57 kg kg^{-1}) were found for the W-W-CF-W-W and W-IM-L-W-YM cropping sequences (Figure 1B,C).

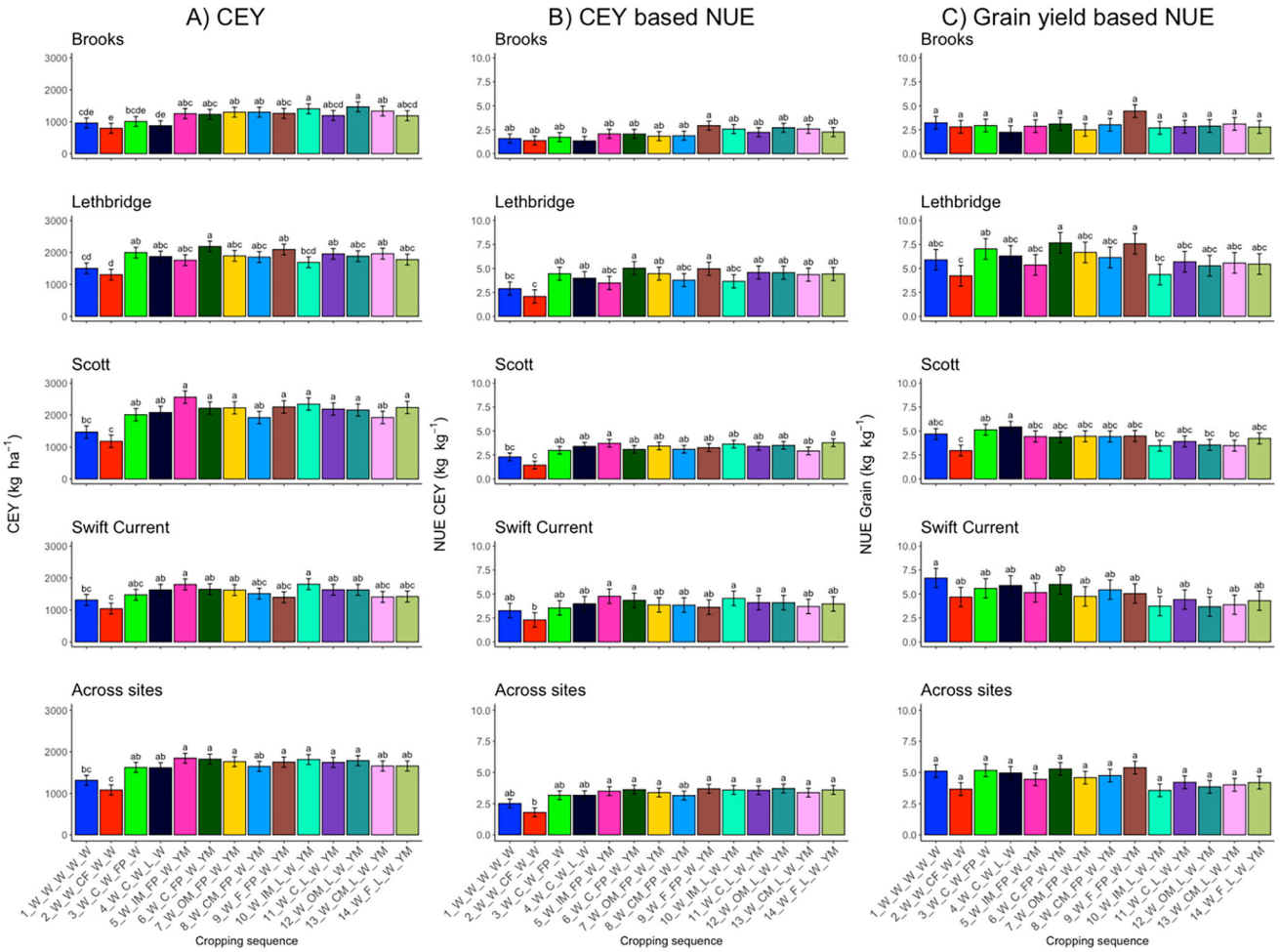


FIGURE 1 Canola equivalent yield, and canola equivalent and grain yield based nitrogen use efficiency from different cropping sequences for each site and across sites in the Canadian prairies. The letters represent the significant difference among the crop sequences within the corresponding year using the Tukey method with $\alpha = 0.05$ (95% confidence interval) following linear mixed models. Bars with the same letters are not statistically different. C, canola; CEY, canola equivalent yield; CF, chemical fallow; CM, camelina; F, flax; FP, field pea; IM, industrial mustard; L, lentil; NUE, nitrogen use efficiency; OM, oriental mustard; W, spring wheat; YM, yellow mustard.

On average across sites, sequences that included oilseed crops and FP (W-IM-FP-W-YM, W-C-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, and W-F-FP-W-YM) had significantly ($p < 0.01$) higher NUE_{CEY} but statistically comparable NUE_{Grain} compared to W-W-W-W-W (Table 6). However, sequences with oilseed crops and lentil (W-IM-L-W-YM, W-C-L-W-YM, W-OM-L-W-YM, W-CM-L-W-YM, and W-F-L-W-YM) had significantly ($p < 0.001$) higher NUE_{CEY} and NUE_{Grain} compared to W-W-W-W-W (Table 6). Furthermore, it was found that the conventional diversified sequences (W-C-W-FP-W and W-C-W-L-W) had statistically similar ($p > 0.05$) NUE_{CEY} but significantly ($p < 0.05$) higher NUE_{Grain} than those with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, W-F-FP-W-YM, W-IM-L-W-YM, W-OM-L-W-YM, W-CM-L-W-YM, and W-F-L-W-YM) (Table 6). Including FP in the cropping sequence with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, and W-F-FP-W-YM) resulted in statistically comparable ($p > 0.05$) NUE_{CEY} compared to lentil (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, and W-F-FP-W-YM), but NUE_{Grain} was significantly ($p < 0.01$) higher with FP than lentil in the sequence (Table 6). Moreover, there were no significant differences ($p > 0.05$) in NUE_{CEY} and NUE_{Grain} between sequences with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, W-IM-L-W-YM, W-OM-L-W-YM, and W-CM-L-W-YM) and those with canola (W-C-FP-W-YM and W-C-L-W-YM) (Table 6).

3.3 | Effects of stubble on subsequent crops in the cropping sequences

In this study, we were particularly interested in the effect of the oilseed crop stubbles on the yield of the subsequent pulse crops and spring wheat following the pulses. Oilseed crop

TABLE 6 Planned contrast analysis to distinguish specific cropping sequence groups and their impacts on canola equivalent yield, and canola equivalent and grain yield based nitrogen use efficiency.

Contrasts (planned comparisons)	CEY		NUE_{CEY}		NUE_{Grain}	
	t ratio	*p* value	t ratio	*p* value	t ratio	*p* value
Continuous wheat vs. field pea rotated with oilseed crops (Cropping sequence 1 vs. cropping sequences 5, 6, 7, 8, and 9)	−4.419	< 0.001***	−2.866	0.0042**	0.462	0.6444^{ns}
Continuous wheat vs. lentil rotated with oilseed crops (Cropping sequence 1 vs. cropping sequences 10, 11, 12, 13, and 14)	−4.084	< 0.001***	−3.165	0.0016**	2.378	0.0176*
Canola vs. minor oilseed crops (Cropping sequences 6 and 11 vs. cropping sequences 5, 7, 8, 10, 12, and 13)	0.413	0.6800^{ns}	0.565	0.5719^{ns}	1.502	0.1333^{ns}
Conventional diversified systems with canola vs. diversification with minor oilseed crops (Cropping sequences 3 and 4 vs. cropping sequences 5, 7, 8, 9, 10, 12, 13, and 14)	1.625	0.1045^{ns}	1.360	0.1740 ^{ns}	−2.058	0.0398*
Field pea vs. lentil rotated with minor oilseed crops (Cropping sequences 5, 7, 8, and 9 vs. cropping sequences 10, 12, 13, and 14)	−0.351	0.7256^{ns}	0.638	0.5235 ^{ns}	−2.854	0.0044**

Note: Cropping sequence 1: W-W-W-W-W, 2: W-W-CF-W-W, 3: W-C-W-FP-W, 4: W-C-W-L-W, 5: W-IM-FP-W-YM, 6: W-C-FP-W-YM, 7: W-OM-FP-W-YM, 8: W-CM-FP-W-YM, 9: W-F-FP-W-YM, 10: W-IM-L-W-YM, 11: W-C-L-W-YM, 12: W-OM-L-W-YM, 13: W-CM-L-W-YM, and 14: W-F-L-W-YM.
Abbreviations: C, canola; CEY, canola equivalent yield; CF, chemical fallow; CM, camelina; F, flax; FP, field pea; IM, industrial mustard; L, lentil; NUE, nitrogen use efficiency; OM, oriental mustard; W, spring wheat; YM, yellow mustard.
*, **, and *** denote significance at the 0.05, 0.01, and 0.001 probability levels, respectively. ^{ns} represents not significant at the 0.05 probability level.

stubbles had no significant effect ($p > 0.05$) on FP or lentil grain yield at any of the sites or across sites, except at Lethbridge, where lentil grain yield was significantly higher on OM than flax stubble (Figure 2). In addition, spring wheat grain yield following the pulses was also similar ($p > 0.05$) among the sequences at all sites and across sites (Figure 2). However, across sites, the average spring wheat yield following FP (1733.8 kg ha^{-1}) tended to be higher than that following lentil (1548.8 kg ha^{-1}), which was both preceded by minor oilseed crops.

In 2020, spring wheat yields and NUE_{Grain} were similar on canola and spring wheat stubbles at all sites, and across sites (Figure S1). In 2021, spring wheat yield and NUE_{Grain} were not affected by the previous crop stubble at Brooks and Lethbridge, as well as NUE_{Grain} of spring wheat at Swift Current and across sites, but spring wheat grain yield and NUE_{Grain} tended to be higher following FP than lentil across sites (Figure S2). However, spring wheat yields were lower for continuous wheat (W-W-W-W) and W-OM-L-W than on CF (W-W-CF-W) at Scott and across sites, and higher on CF (W-W-CF-W) than W-CM-L-W at Swift Current (Figure S2). The NUE_{Grain} for spring wheat at Scott in 2021 was higher on CF (W-W-CF-W) than continuous wheat (W-W-W-W) and lentil stubble from W-IM-L-W, W-OM-L-W and W-F-L-W (Figure S2). In 2022, spring wheat and YM, respectively, had similar yields and NUE_{Grain} irrespective of the previous stubble (Figure S3).

3.4 | Influence of soil and environmental factors

The first two PCs explained 51.9% of the total variability (PC1 = 34.9% and PC2 = 17.0%; Figure S4) of the response variables. The contribution of the response variables to various PCs and the correlation with the response variables to PC1 and PC2 are presented in Figure 3A,B. The contributions to the variation in CEY and grain yield were similar due to their highly positive correlation (Figure 3A), but the percentage contribution to CEY was slightly higher than that of grain yield. The relative contributions to the variation in NUE_{CEY} and NUE_{Grain} were also similar, again due to a strong positive correlation (Figure 3A). The percentage contribution to NUE_{CEY} was slightly higher than that of NUE_{Grain}, indicating that NUE followed a similar trend compared to CEY. Among the soil and environmental parameters, the contribution to the variations was in the order of average growing season mean air temperature > July mean air temperature > May mean air temperature > sand > August mean air temperature > clay > June mean air temperature > SWC 0–60 cm in spring > August precipitation > total growing season precipitation > mineral N at 0–60 cm in fall > mineral N at 0–60 cm in spring > SOC > June precipitation > extrac. P > July precipitation > SWC at 0–60 cm in fall > May precipitation (Figure 3A and Figures S5–S7). Based on the PCA, clustering of variables into distinct groups

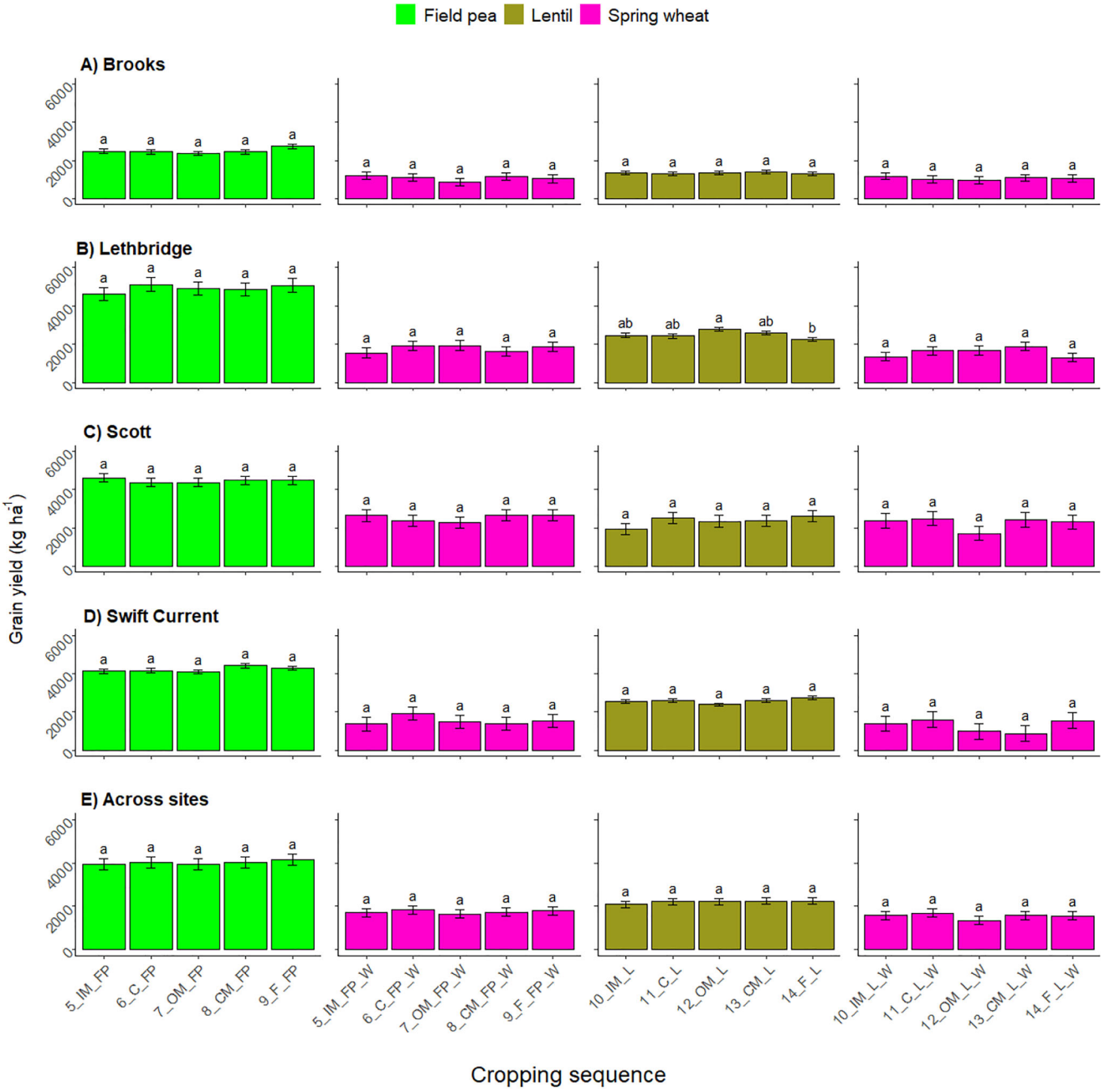


FIGURE 2 Effects of minor oilseed crops on grain yield of subsequent pulses (field pea and lentil) and spring wheat following the pulses. Bars with the same letters for each crop within sites are not significantly different using the Tukey method with $\alpha = 0.05$. The crop sequences represented here are from 2019 to 2020 for field pea and lentil, and 2019 to 2021 for spring wheat. In 2018, spring wheat was grown in all plots. C, canola; CM, camelina; F, flax; FP, field pea; IM, industrial mustard; L, lentil; OM, oriental mustard; W, spring wheat; YM, yellow mustard.

by sites, years, crops, and cropping sequences is shown in Figure S8.

The MANOVA results showed that there were significant differences ($p < 0.001$) among the sites, years, crops, and cropping sequences, with the Pillai Trace test values showing the strength of the significant differences (Table 7). The Pillai value for the cropping sequence was lower (0.6902) than the values for the site (2.5633), year (2.8413), and crop (3.1226). Hence, the highest Pillai value was observed for the crops. The post hoc test of multivariate analysis, that is, LDA ordination plots, showed the actual differences of all the soil and environmental response variables to the explanatory variables, that is, sites, years, crops, and cropping sequences (Figure 4A–D). With respect to sites, we did not find differences in the clustering of soil and environmental response variables between Scott and Swift Current, which significantly differed from Brooks and Lethbridge. In addition, Brooks and Lethbridge significantly differed on the LDA ordination plot (Figure 4A).

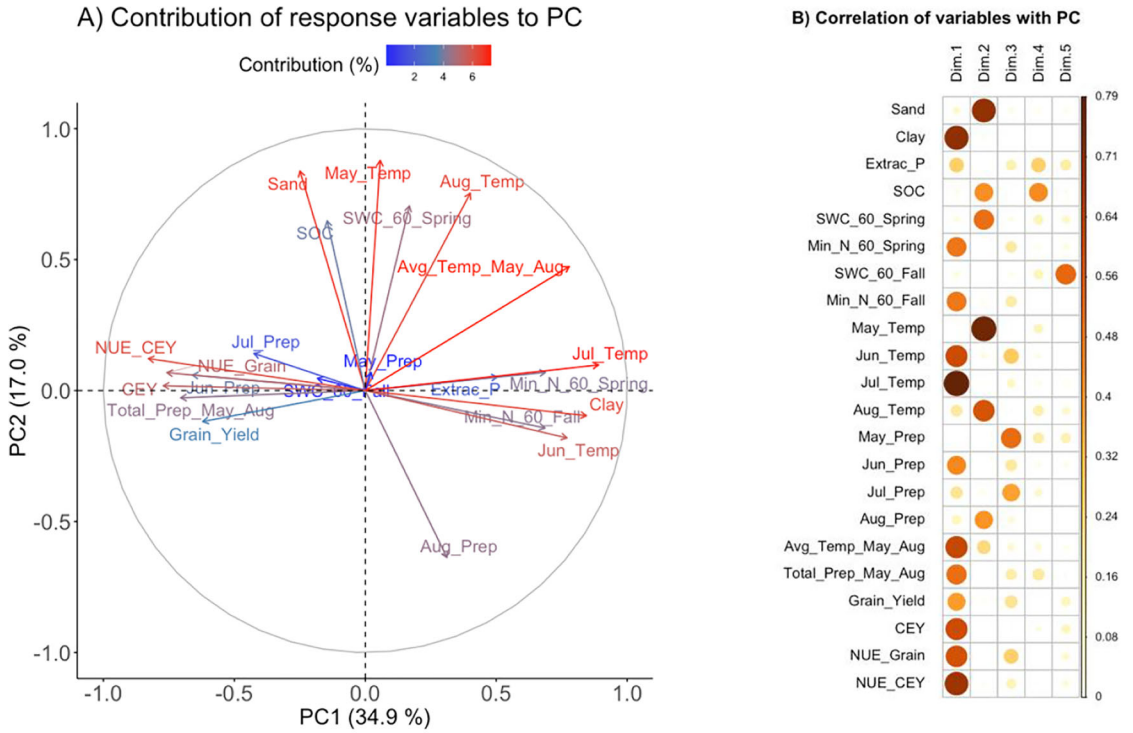


FIGURE 3 Principal component analysis (PCA) examining the interrelationships among productivity in terms of grain and canola equivalent yield, canola equivalent and grain yield based nitrogen use efficiency, and selected soil properties and environmental conditions during the field experiment period of 2019–2022 as vector variables. (A) PCA biplot based on relative importance (%) of measured variables, that is, crop yield, nitrogen use efficiency, selected soil properties, and environmental conditions, to the principal component (PC) (gradient colors) and (B) correlation matrix showing the strength of correlations of each variable contributing to the PC. The ellipses define the 95% confidence intervals. The arrows indicate different variables. The directions and lengths of the arrows indicate the strength of correlations between variables. The angles between arrows reflect their correlations. Variables that are close and form a slight angle have a positive correlation; variables that meet at 90˚ are likely not correlated, and variables that diverge at a large angle close to 180˚ are negatively correlated. The darker shades and larger circles represent stronger correlations. The soil water content and mineral N were from the 0- to 60-cm depth both from spring and fall sampling, while the other soil parameters were from spring sampling at the 0- to 15-cm depth. Precipitations are total, and temperatures are average values. CEY, canola equivalent yield; Dim., dimension; Extrac. P, extractable soil phosphorus; Min. N, mineral nitrogen; NUE, nitrogen use efficiency; PC, principal component; Prep., precipitation; SOC, soil organic carbon; SWC, soil water content; Temp., temperature.

TABLE 7 Multivariate analysis of variance (MANOVA) examining the effects of selected soil properties and environmental conditions on the variability among sites, years, crops, and cropping sequences.

Independent variable	*df*	Pillai	Approximate *F*	Pr (> *F*)
Site	3	2.5633	232.95	<0.001***
Residuals	892			
Year	3	2.8413	710.36	<0.001***
Residuals	892			
Crop	9	3.1226	21.08	<0.001***
Residuals	886			
Cropping sequence	13	0.6902	2.22	<0.001***
Residuals	882			

Note: The MANOVA uses more than one dependent variable; hence, the null hypothesis H0: Group mean vectors are the same for all groups, or they do not differ significantly. Alternative hypothesis H1: At least one of the group's mean vectors are different from the rest. Pillai's trace test was used for the calculations of significant differences for MANOVA, which is then converted to an *F*-statistic when we want to check the significance of the group mean differences.
***denote significance at the 0.001 probability level.

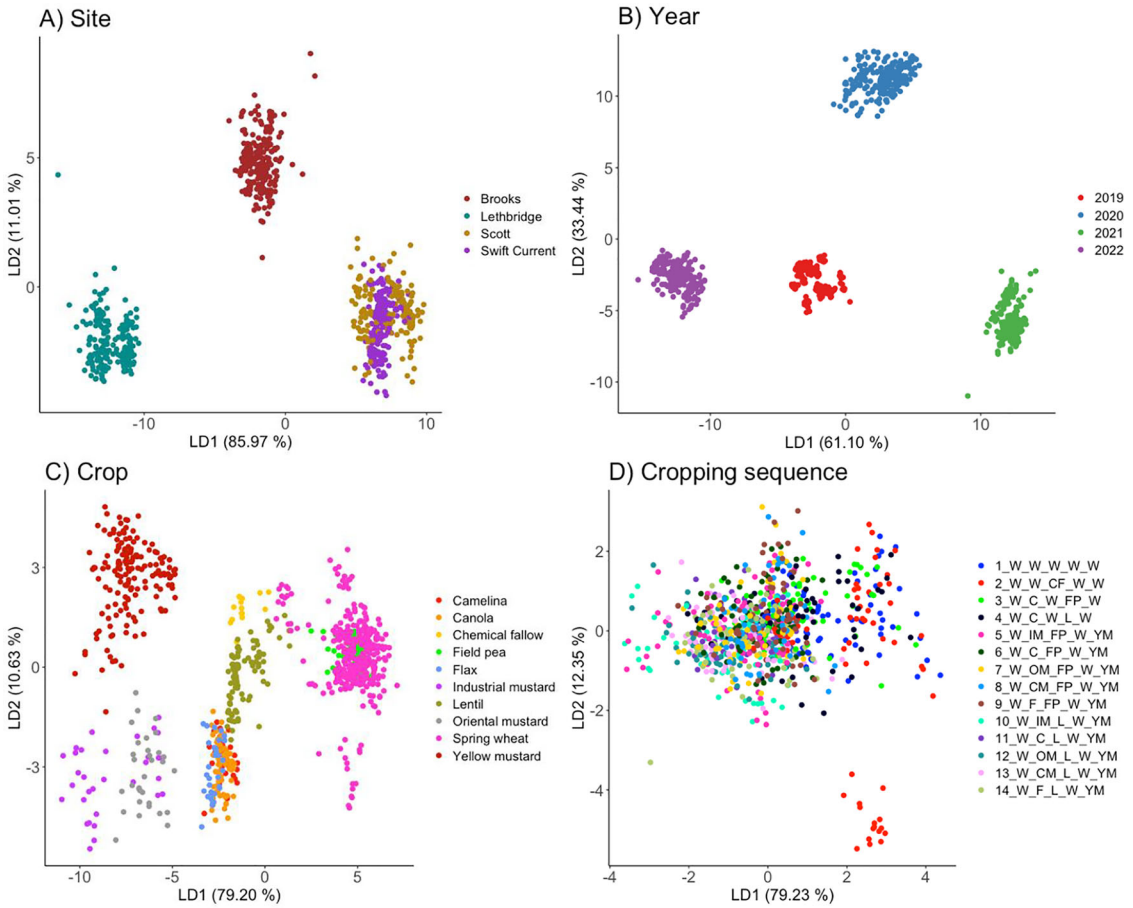


FIGURE 4 Linear discriminant analysis (LDA) as a post hoc test of multivariate analysis of variance (MANOVA) to determine a linear combination of features separating the groups. Scatter plots show the two linear discriminants on the *X* and *Y* axes, and color represents the independent variables: (A) sites, (B) years, (C) crops, and (D) cropping sequences. When the group means are closer on the scatter plots, they represent more similarity, suggesting no significant difference and accepting the null hypothesis. When a group mean is far apart from another on the scatter plots, it means that the group mean vector is significantly different from the other group means, so it rejects the null hypothesis. C, canola; CF, chemical fallow; CM, camelina; F, flax; FP, field pea; IM, industrial mustard; L, lentil; LD, linear discriminants; LDA, linear discriminant analysis; OM, oriental mustard; W, spring wheat; YM, yellow mustard.

In terms of the year, the soil and environmental response variables showed significantly different clustering on the LDA ordination plot, suggesting that each year was different in terms of the measured soil and environmental parameters. With respect to crops or cropping sequence phases, CF was separated on the LDA ordination plots from the other crops or phases included in the cropping sequences. YM also showed a separate clustering on the LDA ordination plot. However, other oilseed crops, that is, canola, camelina, flax, OM, and IM, were clustered together, indicating that similar groups of soil and environmental response variables affected the productivity of these crops. Meanwhile, spring wheat, FP, lentil, flax, and camelina were clustered together, and industrial and OM clustered together on the LDA bi-plot, indicating that the soil and environmental response variables affected these crops similarly. However, in terms of the cropping sequences, all the soil and environmental variables tended to cluster together on the LDA ordination plot, except for the W-W-CF-W-W sequence (Figure 4D).

4 | DISCUSSION

4.1 | Impact of cropping sequence on system productivity

In this study, we used a systems approach based on equivalent yield, CEY in this case, for examining and comparing the productivity of cropping systems, an approach widely used in other cropping system studies (Khanal et al., 2021; K. Liu, Blackshaw, et al., 2019; K. Liu, Johnson, et al. 2019; Mohanty et al., 2024; Singh et al., 2025). While there were significant differences in CEY at all sites and across sites, no single sequence performed the best across all sites, nor did one at any specific site. On average across sites, CEY was statistically comparable between cropping sequences where minor oilseed crops replaced canola and with canola. Contrast analysis showed that across the specific sequences where the minor oilseed crops replaced canola, average canola yields across sites were significantly higher than the corresponding

average minor oilseed crop yield (data not shown). Moreover, grain yields for subsequent crops, such as FP, lentil, spring wheat, and YM, seldom varied among these sequences (Figures S1–S3). Hence, our finding of similar CEY between cropping sequences with canola and when minor oilseed crops replaced canola could be attributed to the higher average grain price for the minor oilseed crops (Table S3) rather than actual grain yield differences. This indicates that the higher canola grain yield was not sufficient to compensate for the higher grain prices of the minor oilseed crops. Elevated grain prices for minor oilseeds like mustards over the last couple of years have increased farmers' interest in these crops in the Canadian prairies. Recently, using data from this study, Khakbazan et al. (2025) found similar net returns between sequences with minor oilseed crops and those with canola. While these findings imply that replacing canola with minor oilseed crops may not adversely impact overall system productivity and profitability in the Canadian prairies, environmental conditions and market trends will influence productivity and profitability.

Canola yields during the study period were much lower than historical averages due to the hot and dry conditions, yet canola yields were higher than minor oilseed crops. The higher canola yields than minor oilseed crops were expected (Gan et al., 2007). However, the higher susceptibility of canola to heat and water stress than other crops such as mustards (Angadi et al., 2000; Gan et al., 2004, 2007), as well as higher grain prices of the minor oilseeds, make them a viable and profitable alternative to canola, particularly under semi-arid conditions. It was suggested that locations with cooler temperatures and consistent precipitation are necessary for high canola yields (Harker et al., 2014). Conversely, Angadi et al. (2008) found inadequate evidence to indicate that mustard is more drought-tolerant than canola. Under irrigated conditions in Nebraska, Pavlista et al. (2012) reported comparable grain yields for canola, camelina, and OM.

Considering the advantages of further diversification of the cropping systems in the Canadian prairies, our study indicated that the minor oilseed crops, such as camelina, IM, OM, YM, and flax, could be suitable alternatives to canola in prairie cropping systems. Although the growing demand for biodiesel feedstock has led to an increase in canola production in the Canadian prairies, camelina, flax, and OM are regarded as alternative oilseed crops with the highest potential for biodiesel production based on yield and oil content (Blackshaw et al., 2011). Moreover, if competition from the market drives canola prices above the threshold for economically viable biodiesel production, minor oilseed crops considered in this study may be included in the cropping sequences to fill the gap (McVetty & Duncan, 2015). However, unlike canola, these minor oilseed crops have fewer options for pest and disease control, which could limit their inclusion in cropping sequences. Moreover, challenges related to flax straw can also hinder greater inclusion of flax into cropping sequences in the Canadian prairies given its low nutrient value, fiber structure, which limits its decomposition and adds unique harvesting issues, and low market options for the straw (Flax Council of Canada, 2019; Zamiri et al., 2024). Overall, our study showed that the replacement of canola with minor oilseed crops did not appear to adversely impact system productivity.

The CEY was higher when FP or lentil was rotated with oilseed crops compared to W-W-W-W-W. The beneficial impact of incorporating pulses into cropping systems is well-known. Pulse crops, such as FP and lentil, contribute additional N through biological N-fixation and provide non-N benefits, such as higher residual soil moisture and breakup of pest and disease cycles, leading to positive effects for subsequent cereal crops (Hossain et al., 2016; St. Luce et al., 2015). Using data from a long-term field experiment, St. Luce et al. (2020) concluded that diversifying cropping systems with pulses (FP and lentil) can consistently produce higher grain and protein yields with lower N fertilizer inputs, potentially reducing negative environmental consequences. Gan et al. (2015) found that replacing summer fallow with pulse crops resulted in a 35.5% increase in overall system production. Previous studies showed that both FP and lentil can positively influence subsequent wheat yield, with FP having a more significant impact than lentil on the cropping systems (K. Liu et al., 2020). L. Liu et al. (2011) observed that FP had more branched roots than lentil, which helped with water and nutrient uptake under stressful conditions, leading to increased grain yield and enhanced productivity of the cropping systems. However, in this study, there were no significant differences in CEY between sequences with FP compared to lentil. Smith et al. (2017) and Khakbazan et al. (2014) reported that inclusion of FP and lentil can enhance farm profitability compared to conventional wheat monoculture systems or systems with no pulse crops. A recent economic analysis by Khakbazan et al. (2025) based on the current study found higher net returns for systems diversified with minor oilseeds and pulses, particularly W-OM-FP-W-YM and W-OM-L-W-YM than W-W-W-W-W and W-W-CF-W-W across sites. Therefore, diversified crop sequences incorporating oilseeds and pulses are more productive and profitable than those systems focused solely on cereals or oilseeds.

As expected, the conventional diversified sequence had higher CEY than W-W-W-W-W and W-W-CF-W-W across sites, further highlighting the critical importance of crop diversification for enhanced productivity and profitability. Moreover, the CEY between the conventional diversified systems, with cereal, canola, and pulses, and diversification with minor oilseed crops across sites were statistically comparable. In comparison to the conventional diversified sequences, diversified sequences with minor oilseed crops replaced canola with a minor oilseed crop and spring wheat grown in the fourth year with YM. Hence, the conventional diversified sequences had three spring wheat phases, while

the diversified with minor oilseed crops had two spring wheat phases and two minor oilseed crop phases. This suggests that these changes to the conventional diversified cropping sequences did not adversely affect productivity on a CEY basis, partly due to the higher grain prices for the minor oilseed crops. Nevertheless, our study showed that a conventional diversified cropping sequence with spring wheat, canola, and pulses is effectively adapted to the Canadian prairie conditions; however, sequences with spring wheat, minor oilseed crops, and pulses performed similarly with respect to CEY.

The W-W-CF-W-W resulted in the lowest CEY compared to all other evaluated crop sequences. Moreover, CEY for W-W-W-W-W was statistically comparable with that of the W-W-CF-W-W sequence at all and across sites. Summer fallow integrated into cropping sequences aims to conserve soil moisture and manage weeds, particularly in arid to semi-arid regions, while enhancing subsequent crop yields (Black & Power, 1965; Fenster et al., 1965; Wicks & Smika, 1973). The absence of yield in the fallow year could account for the low CEY for the W-W-CF-W-W sequence, while for W-W-W-W-W, it was probably related to low spring wheat yields and less crop diversity. Our findings indicate that spring wheat yield following CF was insufficient to compensate for the loss of yield during the fallow phase. Smith et al. (2017) reported that grain yield increased as the frequency of fallow decreased. Frequent fallow in crop sequences can also lead to long-term deterioration of soil health and reduction in SOC content due to low crop residue input (Lemke et al., 2012; Maillard et al., 2018; St. Luce et al., 2024). However, fallow has been replaced, for the most part, by continuous and diversified cropping with direct seeding, a more sustainable practice in the Canadian prairies (Bueckert & Clarke, 2013; Liu & Martin, 2024; May et al., 2020).

4.2 | Impact of cropping sequence on NUE of the system

NUE is crucial for enhancing cropping system productivity, sustainability, and profitability, especially under changing climate conditions, as N is essential for plant growth but is also a major source of greenhouse gas emissions (Govindasamy et al., 2023). On a system level, we observed significant differences in NUE_{CEY} and NUE_{Grain} at all experimental sites except at Brooks for NUE_{Grain}, which could be attributed to site-specific conditions and varying average N fertilizer application rates and annual crop yields. Our results align with earlier research, which showed that NUE tends to decline as N fertilizer application rates increase (Campbell et al., 1993; Wen et al., 2023). Moreover, results indicated that NUE_{CEY} and NUE_{Grain} varied significantly among different sequences, and no single sequence consistently performed the best across all sites. Globally, the lack of leguminous crops in cropping systems was shown to reduce NUE (Govindasamy et al., 2023). In addition, different crops or varieties have varying abilities for N uptake per unit of biomass production; therefore, varying N uptake and assimilation can lead to differences in NUE among cropping sequences (Dong & Lin, 2020).

In our study, NUE_{Grain} was significantly lower in the diversified sequences with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, W-F-FP-W-YM, W-IM-L-W-YM, W-OM-L-W-YM, W-CM-L-W-YM, and W-F-L-W-YM) compared to conventional diversified sequences (W-C-W-FP-W and W-C-W-L-W). However, CEY and NUE_{CEY} were similar between them. Although average N applied in the conventional diversified sequences (46 kg N ha^{-1}) was slightly higher than the diversified with minor oilseeds (39 kg N ha^{-1}), the higher grain yield in the conventional diversified could partly account for this. The higher average grain yield in the conventional diversified was due to higher canola grain yields coupled with having three spring wheat phases, while the diversified with minor oilseeds had two minor oilseed crop phases with lower grain yields. As mentioned previously, N fertilizer rates were determined based on fall soil tests and target yields starting only in 2021. While all crops received the same amount of N fertilizer in 2019, average grain yields and NUE_{Grain} were higher for the conventional diversified (canola) than diversified with the minor oilseed crops in 2019 (data not shown). In 2020, average grain yield was higher for the conventional diversified (spring wheat) than the diversified with minor oilseeds (pulses), but there were no significant differences in NUE_{Grain} (Figure S1; contrast not shown). In 2021, both average grain yield and NUE_{Grain} were similar between the conventional diversified (pulses) and the diversified with minor oilseeds (spring wheat) (Figure S2; contrast not shown). However, in 2022, both average grain yield and NUE_{Grain} were much higher for the conventional diversified (spring wheat) than the diversified with minor oilseeds (YM) (Figure S3; contrast not shown). Hence, while we found lower N requirements and therefore cost in the diversified with minor oilseeds, which agrees with Khakbazan et al. (2025), the lower yields in the diversified with minor oilseed crops reduced the NUE_{Grain}. Development and implementation of N fertilizer rates based on target yields of specific crops and soil test prior to 2021 would have provided a more thorough understanding of the impact on NUE. However, as observed for CEY, both NUE_{CEY} and NUE_{Grain} were statistically comparable between sequences with minor oilseed crops (W-IM-FP-W-YM, W-OM-FP-W-YM, W-CM-FP-W-YM, W-IM-L-W-YM, W-OM-L-W-YM, and W-CM-L-W-YM) and sequences with canola (W-C-FP-W-YM and W-C-L-W-YM).

Incorporating pulses in cropping sequences is a sustainable way to reduce N fertilizer use and increase NUE, as it provides a significant amount of plant-available N through

biological N fixation and mineralization of N-rich residues from both above and below ground (Arcand et al., 2014; Beckie & Brandt, 1997), and therefore boosts yields of subsequent crops, though the benefits vary by pulses, the following crop, and site conditions (St. Luce et al., 2015; Walley et al., 2007). This could partly explain the significantly higher NUE_{CEY} and NUE_{Grain} for sequences with lentil and minor oilseed crops compared to the W-W-W-W-W sequence. However, only NUE_{CEY} was significantly higher for sequences with FP and minor oilseed crops compared to W-W-W-W-W. The higher NUE_{Grain} for the sequences with minor oilseed crops and FP compared to lentil could be attributed to the higher FP yields than lentil.

4.3 | Impact of crop stubbles on the grain yield and NUE of the subsequent crops

Grain yields and NUE_{Grain} were not significantly impacted by the previous stubble, except in some specific situations. Importantly, FP and lentil grain yields were not affected by the oilseed crop stubbles, except for lentil at Lethbridge. Brassicaceae crops, such as canola and mustards, are known to have allelopathic effects due to the production of glucosinolates and their breakdown products, such as iso-thiocyanates and thiocyanates (Nguyen et al., 2020). These compounds vary by Brassicaceae species, with canola generally having the lowest levels, which may adversely impact biological N fixation and yield of pulses (Kirkegaard & Sarwar, 1998; Mocniak et al., 2023; Sun et al., 2019). Our results suggest that the minor oilseed crops had no adverse impact on FP and lentil grain yield. A study by Gan et al. (2009) showed that soil water use and distribution in the soil profile were generally similar for canola and mustard, but both used more water than flax. In our study, SWC in spring and fall was similar among the oilseed crops (data not shown).

In our study, we did not find substantial differences in spring wheat grain yields and NUE_{Grain} following FP than lentil. This could partly be explained by the extremely hot and dry conditions in 2021 when spring wheat was grown. It is widely recognized that pulse crops in cropping sequences significantly benefit soil N (Gan et al., 2010; St. Luce et al., 2016; Walley et al., 2007) and soil water (Angadi et al., 2008; Cutforth et al., 2013) for subsequent crops. A global meta-analysis by Lasisi and Liu (2023) found that different types of pulses influenced subsequent wheat yields in the following order: lentil had the greatest impact, followed by FP, with chickpeas having a similar effect as FP. Therefore, the authors concluded that pulses, especially pea and lentil, can help decrease reliance on synthetic N fertilizer and lower environmental pollution, benefiting both farmers and the environment. Niu et al. (2017) found that residual soil N and water left after pea and lentil cultivation contributed to 30% of the yield difference in wheat grown in pulse-inclusive rotations compared to continuous wheat. Hence, it was suggested that the improved water use efficiency in pulse-inclusive wheat systems highlights the advantages of crop diversification with pulses, which can help conserve water and boost yields during drought conditions. The higher spring wheat yield on CF than spring wheat stubble across sites and at Scott in 2021 was in agreement with previous findings and could be due in part to higher soil moisture and soil N supply from CF (Campbell et al., 2008; Gan et al., 2015; St. Luce et al., 2020). Spring SWC in 2021 following CF was significantly or numerically higher than other phases at all sites (data not shown). The similar NUE_{Grain} observed for YM in 2022 was likely due to the very low yields recorded, even though N rates varied slightly among cropping sequences.

4.4 | Impacts of soil and environmental parameters on the cropping sequence productivity

Among the environmental variables, the growing season (May to August) mean air temperature contributed most to the variation in CEY, grain yield, NUE_{CEY}, and NUE_{Grain} across the sites and years, followed by the growing season precipitation. The CEY (as well as grain yield) was highly and positively correlated with the growing season precipitation, which agrees with other studies given the soil moisture-limited nature of the study sites (Lychuk, Moulin, Izaurralde, et al., 2017; Millett et al., 2009). A recent study by Wen et al. (2024) showed that precipitation and N management accounted for 25% and 21% of yield variations, respectively, and are the primary factors influencing cropping system productivity in the Canadian prairies. However, as expected, variations in soil and environmental factors varied across sites due to temporal and spatial differences. The 48.1% unexplained variation in our study may be associated with other environmental and soil variables not measured, including N mineralization during the growing season, as well as crop management factors, pests, and diseases. For example, all sites contained both grassy and broadleaf weeds in all years (Table S2), which could have affected productivity, despite the application of recommended herbicides for weed control. In 2021, Brooks experienced an infestation of root rot in lentil in the W-C-W-L-W sequence. Furthermore, the field experiment in our study was mainly conducted under rain-fed conditions in the semi-arid Canadian prairies; however, a small amount of irrigation was applied at Brooks and Lethbridge to enhance crop establishment. The Prairie region in Canada typically experiences substantial water shortages due to low rainfall and high evapotranspiration (Mapfumo et al., 2023). We note that all of the sites experienced moderate to severe drought during the study period, with below normal precipitation (Table 4).

The dry conditions at seeding in most years and sites adversely affected crop emergence (Table S4) and establishment, further impacting crop growth, followed by high temperatures during and after flowering, which negatively affected yields, particularly in canola and mustard crops. A study in the Canadian prairies identified precipitation in the pre- and early-growing seasons as a crucial factor affecting crop yields (Meng et al., 2017). In a long-term cropping systems study in the Canadian prairies, 22% of yield variation was explained by April precipitation (Lychuk, Moulin, Lemke, et al., 2017).

Climate variation is a significant contributor to variations in global crop yields (Ray et al., 2015). In addition to the growing season precipitation, precipitation in June and July, which is typically around flowering for most crops, also strongly correlated with CEY and grain yield. This finding re-emphasizes the critical nature of not just precipitation amounts but also its timing and distribution in the Canadian prairies, where soil moisture is the most limiting factor (Campbell et al., 2007). Similarly, Garnett et al. (2006) found that precipitation in June and July was most strongly related to spring wheat yield in the Canadian prairies, while precipitation from May to July most strongly influenced canola yields. In our study, precipitation and mean air temperature in June and July influenced both canola and spring wheat yields. In addition, the mean air temperature from May to August had a significant impact on both crops. The interaction between crops and the environment is complex; however, increasing crop diversity could help reduce the impact of weather variations and improve yield stability (Gaudin et al., 2015; K. Liu, Blackshaw, et al., 2019).

In a dry year, cropping sequence had a more considerable impact on wheat yield compared to the preceding crops, explaining 35% and 25% of yield variation, respectively, while in a wet year, both cropping sequence and preceding crops were similarly important (Niu et al., 2017). In our study, the cropping sequence as a system did not show significant variation based on the soil and environmental variables considered. However, there was a significant variation when considering the specific crops, particularly in the similarities in clustering or grouping of oilseeds, pulses, and spring wheat. It was observed that canola thrives in higher-yielding environments than mustards and yields more when it receives sufficient and timely rainfall during the growing season (Gan et al., 2004; Gunasekera et al., 2006). However, minor oilseed crops, with varying yield potentials and tolerance to drought and heat stresses when seeded early and with adequate N fertility, offer an opportunity to diversify current oilseed-based cropping systems and improve oilseed stability in the Canadian prairies (McKenzie et al., 2006). OM was found to have higher water use efficiency than canola, making it better suited to challenging growing conditions (Wright et al., 1996, 1995), such as low precipitation and high temperatures, compared to canola in the Canadian prairies (Miller et al., 1998). Other studies on the Canadian prairies indicated that OM and YM exhibit greater resistance to drought than canola, particularly during the flowering phase (Angadi et al., 2004, 2000; Blackshaw et al., 2011; Gan et al., 2004). It is crucial to develop innovative cropping strategies to boost yield and ensure the sustainability of the cropping systems in moisture-limited environments. Promotion and adoption of cropping system diversification is vital to overcoming both abiotic and biotic stresses, especially in the face of climate change, thereby strengthening cropping system resilience in the Canadian prairies (Martens et al., 2015). Cropping systems with diverse crop species can improve yield consistency by decreasing the likelihood of yield reductions during adverse environmental conditions like heat and drought (Gaudin et al., 2015).

Among the soil parameters, soil texture (sand, clay) contributed the most to the overall variation in CEY and grain yield, followed by SWC in spring, mineral N in the fall and spring, and SOC. Meanwhile, extrac. P and SWC in the fall showed less contribution to the variation. These findings further highlight the critical importance of soil moisture in the Canadian prairies for crop production and the role that soil texture plays in soil moisture dynamics. Soil tests for developing N fertilizer recommendations in the Canadian prairies are predominantly conducted in the fall. The lower contribution of mineral N in the fall was likely due to the mostly dry conditions over the study period. Niu et al. (2017) reported that soil water and soil N explained up to 30% of the yield and biomass variation of the cropping sequence effect with wheat and pulse crops; however, the magnitude of the variation differed across sites. In the semi-arid Canadian prairies, after precipitation or soil moisture, N availability is the second most limiting factor for crop production (Campbell et al., 2008; Kröbel et al., 2012). Moreover, it is widely recognized that the impact of N on crop productivity in this semi-arid region largely depends on soil moisture (Campbell et al., 2008; Kröbel et al., 2012). The quantity of water retained in the soil profile in the spring plays a crucial role in germination, crop establishment, and the initial phases of plant development (Gan et al., 2009). At the end of the growing season, the soil water and mineral N remaining in the soil profile in the Canadian prairies (referred to here as SWC and soil mineral N content in the fall) are beneficial for crops seeded in the subsequent season (Gan et al., 2010; Walley et al., 2007). Diversifying cropping systems by including grain legumes in cereal-based cropping sequences can improve soil water conservation and increase system productivity (Gan et al., 2015). Furthermore, diversified cropping systems can enhance SOC levels, increase microbial activity and diversity, enhance aggregate stability, and improve nutrient and moisture retention, thereby promoting overall soil health (Iheshiulo et al., 2023), which also has a profound impact on cropping system productivity.

5 | CONCLUSION

The main aim of this study was to examine the impact of cropping sequence diversification with minor oilseed crops on system productivity and NUE in the semi-arid Canadian prairies. We found significant cropping sequence effects on CEY, $NUE_{CEY,}$ and NUE_{Grain} across sites and at all sites (except NUE_{Grain} at one site), yet no single cropping sequence consistently outperformed the others at all sites, suggesting the responses were site-specific. The CEY and NUE for cropping sequences involving FP or lentil together with oilseed crops and spring wheat were significantly higher than W-W-W-W-W (except NUE_{Grain} for those with lentil), which was predominantly lower at all sites along with W-W-CF-W-W. The NUE_{Grain} for the conventional diversified system with canola, pulses, and spring wheat was significantly higher than for those incorporating minor oilseed crops, but CEY and NUE_{CEY} were statistically comparable between these cropping sequences. Moreover, the minor oilseed crops had no adverse impact on grain yields of subsequent FP and lentil or spring wheat following the pulses. There were also no substantial differences in CEY and NUE_{CEY} between sequences with FP compared to lentil, but NUE_{Grain} was higher with FP than lentil in the sequence. However, on average across sites, spring wheat yields following FP tended to be higher than those following lentil. Among several influential environmental factors, the average growing season (May to August) mean air temperature, and July, May, August, and June mean air temperatures significantly impacted the productivity and NUE of the cropping sequences, followed by soil factors including texture (sand and clay) and SWC in spring.

Our findings suggest that diversifying current cropping systems by introducing minor oilseed crops can lower N fertilizer requirements and costs compared to conventional diversified sequences without reducing overall system productivity on a CEY basis. Moreover, this study showed that replacing canola with a minor oilseed crop did not adversely affect system productivity and NUE in the semi-arid Canadian prairies. Developing innovative cropping sequence strategies is essential for increasing yield and ensuring the sustainability of cropping systems in moisture-limited prairie environments. However, this study was only conducted over a 5-year period under mild to severe drought conditions, and N fertilizer rates based on soil tests were only implemented from the third year. Hence, a longer term study with more diverse sites and environmental conditions coupled with optimized N rates would help to confirm these findings and provide more robust evidence. Furthermore, research on the soil feedback, including SOC, nutrients, and water dynamics, is also warranted.

AUTHOR CONTRIBUTIONS

Shayeb Shahariar: Formal analysis; software; visualization; writing—original draft; writing—review and editing. **Mervin St. Luce**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; supervision; validation; writing—original draft; writing—review and editing. **Manjula Bandara**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; writing—review and editing. **Charles M. Geddes**: Conceptualization; data curation; funding acquisition; investigation; methodology; writing—review and editing. **Kui Liu**: Data curation; investigation; writing—review and editing. **Prabhath Lokuruge**: Data curation; investigation; writing—review and editing. **Mohammad Khakbazan**: Data curation; writing—review and editing. **Brian McConkey**: Conceptualization; funding acquisition; methodology; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be made available upon reasonable request.

ORCID

Shayeb Shahariar https://orcid.org/0000-0001-6559-0548
Mervin St. Luce https://orcid.org/0000-0002-2805-9587
Charles M. Geddes https://orcid.org/0000-0001-8088-224X
Mohammad Khakbazan https://orcid.org/0000-0002-0782-3443

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SUPPORTING INFORMATION

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