frontiers | Frontiers in Agronomy

TYPE Original Research
PUBLISHED 09 February 2026
DOI 10.3389/fagro.2025.1732922

OPEN ACCESS

EDITED BY
Stéphane Cordeau,
UMR Agroécologie, France

REVIEWED BY
Amit Anil Shahane,
Central Agricultural University, India
Huong T. X. Nguyen,
McGill University, Canada

*CORRESPONDENCE
Nityananda Khanal
nityananda.khanal@agr.gc.ca

†Retired

RECEIVED 26 October 2025
REVISED 06 December 2025
ACCEPTED 11 December 2025
PUBLISHED 09 February 2026

CITATION
Bhattarai K, Khanal N, Thilakarathna MS, Lupwayi NZ, Rahman N, Otani J, Shrestha B, Lemke RL and Kroebel R (2026) Crop diversification with high-value perennial seed crops drives profitability in crop rotations in northwestern Canada.
Front. Agron. 7:1732922.
doi: 10.3389/fagro.2025.1732922

Crop diversification with high-value perennial seed crops drives profitability in crop rotations in northwestern Canada

Keshav Bhattarai[1,2], Nityananda Khanal[1*], Malinda S. Thilakarathna[2], Newton Z. Lupwayi[3†], Noabur Rahman[1], Jennifer Otani[1], Bharat Shrestha[1], Reynald L. Lemke[4] and Roland Kroebel[3]

[1]Agriculture and Agri-Food Canada, Beaverlodge Research Farm, Beaverlodge, AB, Canada, [2]Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, AB, Canada, [3]Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, AB, Canada, [4]Agriculture and Agri-Food Canada, Saskatoon Research and Development Centre, Saskatoon, SK, Canada

Cropping system diversification is considered a rational management practice for improving resource-use efficiency, enhancing productivity, and optimizing farm returns in the face of climate change. However, few studies have concurrently explored the productivity, profitability, and nitrogen use efficiency (NUE) of cropping systems diversified with perennial forage seed crops. This study, conducted on dark gray Luvisolic soil in the Peace River region of northwestern Canada from 2013 to 2024, sought to address this gap. A field experiment, arranged in a split-plot design, comprised eight cropping sequences as main plots and three nitrogen (N) levels (0, 45, and 90 kg N ha^{-1}) as sub-plots. The cropping sequences included two perennial legumes (red clover and alsike clover), three perennial grasses (creeping red fescue, meadow bromegrass, and timothy), and four annual field crops (wheat, canola, pea, and barley). Productivity was evaluated based on seed yield and expressed as canola equivalent yield (CEY), while gross revenue and gross margin were used as profitability metrics. Based on CEY and aboveground biomass yield, NUE was also assessed for uniform comparison among cropping sequences. Intermittent inclusion of red clover (a perennial legume) and meadow bromegrass (a perennial vernalizing grass) in the cropping sequence increased CEY, gross revenue, gross margin, and agronomic NUE by 95-108%, 118-174%, 191-255%, and 21–77%, respectively, compared with alternating annual wheat-canola sequences across three N fertility levels. The higher seed price of red clover and greater seed yield and price of meadow bromegrass during their production phases provided opportunities to capitalize on local market demands. The N fertilization at 45 kg N ha^{-1} improved the yield and profitability across all cropping sequences, whereas the 90 kg N ha^{-1} rate did not result in significant economic benefits in comparison. Our results provide evidence that forage seed crop-based cropping systems have the potential to reduce reliance on external N inputs and enhance the economic efficiency of production systems.

KEYWORDS

annual crops, canola equivalent yield, cropping sequence, gross margin, nitrogen use efficiency, perennial crops

1 Introduction

Global food security is continually threatened by climate change with increased crop vulnerability to extreme weather events, disease, pest and weed infestation, and soil productivity reduction (Campbell et al., 2016; Fletcher et al., 2021; Mosier et al., 2021; Rajput et al., 2024). Optimizing crop productivity and maintaining soil and environmental health can make the food system more resilient and sustainable (Bowles et al., 2020; Hassan et al., 2022). In recent years, advancements in technology, the availability of high-yielding crops and varieties, and the use of chemical inputs have resulted in enhanced production efficiency (Qaim, 2020; Khan et al., 2021; Hemathilake and Gunathilake, 2022). However, chemical-dependent production practices increase production costs and create environmental and ecological issues, such as increased greenhouse gas emissions, soil degradation, loss of biodiversity, and the emergence of resistant pests (Yang et al., 2020; Brühl and Zaller, 2021; Brunharo et al., 2022; Menegat et al., 2022). Addressing these issues requires a multifaceted systemic approach that integrates beneficial management practices (BMPs), including diverse cropping systems, to regenerate soil health and improve nutrient cycling. Crop diversification offers excellent potential for improving farm productivity and profitability by reducing the reliance on agrochemicals, thereby lowering plant protection and nutrition costs (Harkness et al., 2021; Nilsson et al., 2022; Yang et al., 2024). However, diversification requires understanding of agronomic needs of crop species and may demand careful planning to meet management requirements.

Cropping system diversification can be practiced in both space and time through cultivar mixture, intercropping, cover crops, agroforestry, livestock integration, and crop rotation (Martens et al., 2013). In western Canada, annual crop rotations with cereals, oilseeds, and legumes are the most common due to their straightforward adoption and availability of modern farm equipment for large-scale farming and economic benefits (Zentner et al., 2002; Liu C. et al., 2022). Nevertheless, when rotations are repeatedly limited to a narrow set of crops over the long term, they risk undermining soil health and essential ecosystem functions required to sustain crop productivity (Chahal et al., 2021; Bogužas et al., 2022; Cappelli et al., 2022). Conversely, incorporating a greater number of crop species in rotations, both by reducing the frequency of planting the same crop and through practices such as intercropping, can safeguard soil health and enhance long-term productivity. A comprehensive study recently conducted across the Prairies confirmed the benefits of diversified rotations; however, the productivity performance of different rotations varied greatly by region. For example, rotations dominated by oilseeds showed higher yields in relatively humid areas, whereas rotations dominated by legumes appeared more resilient and maintained productivity in the drier areas (Timlick, 2023). Rotational diversification, when aligned with local soil and climatic conditions and market demand, offers growers reduced production risks, improved soil health, and greater resilience despite productivity uncertainties (Roesch-McNally et al., 2018; Brannan et al., 2023; Liang et al., 2023).

Adaptation of perennial cool-season forages and turfgrasses to the Luvisolic soils and cool, continental climate of the Peace River region allows these crops to be integrated into annual cropping sequences for the production of high-quality seeds (Khanal, 2022). Once established, perennial stands produce multi-year seed yields, despite a progressive decline over time, and generate economic benefits by reducing the need for annual replanting and lowering both operational and input costs (Khanal et al., 2021). In addition, perennial forages provide continuous ground coverage over the growing season, and their extensive root system protects soil from erosion and improves soil structure (Martens et al., 2015; Schlautman et al., 2021; Picasso et al., 2022). This is particularly important in the erosion-prone areas of the Peace River region, where preserving soil health is critical for long-term agricultural productivity (Acton and Gregorich, 1995; Lavkulich and Arocena, 2011). Therefore, diversifying cropping systems with perennial forages would provide a significant advantage over traditional annual crop rotations in terms of productivity, profitability, soil health, and ecosystem benefits.

Although increasing diversity is believed to improve ecological functions and landscape resilience, its effect on farm income stability remains largely unknown, particularly in the Peace River region of western Canada. Furthermore, the complex interactions between local soil conditions and environmental factors that influence forage seed yield are not well understood, which adds to the challenge of optimizing production. As a result, perennial forage seed production areas are declining in this region (Khanal, 2022). Several agricultural management options, such as crop choices, planting patterns, and balanced N fertilization, might help optimize the productivity and profitability of forage seed crop-based diversified cropping systems. These considerations prompted the hypothesis that integrating perennial forage seed crops into simplified annual crop rotations will enhance system productivity, nitrogen use efficiency (NUE), and long-term economic profitability compared to conventional rotation practices. To test the hypothesis, a long-term field experiment was conducted over ten years to evaluate the cumulative systems productivity and relative economic advantages of including forage seed crops within annual cash crop rotations. The goal was to identify the economically profitable cropping sequences suited to the continental climate of the Peace River region of Canada.

2 Materials and methods

2.1 Description of the experimental site

The field experiment was initiated in 2013 at the Agriculture and Agri-Food Canada (AAFC)'s Beaverlodge Research Farm (55°12' N 119°24' W), located in northwestern Alberta, Canada. The site features a slope gradient of 2.5% and average elevation of 745 m. The predominant soil at the site was a dark gray Luvisol developed from lacustro-till and glacial-lacustrine deposits (Broersma et al., 1997). Soil analysis of initial soil samples taken in 2013 at depths of 0-15, 15-30, and 30–60 cm depths showed organic matter content of 5.5, 4.3, and 3.6%; pH values of 5.43, 6.13, and 6.43; and bulk densities of 1.3, 1.5, and 1.6 g cm^{-3}, respectively (Khanal et al., 2021). Soils at the surface layer (0–15 cm) were loamy in texture (31.3% sand, 46.0% silt, and 22.7% clay), and the sub-surface layer (15–30 cm) had a clay loam texture (28.1% sand, 36.1% silt, and 35.8% clay). The experimental region has a continental climate with a mean annual precipitation of 435 mm based on the 30-year average of weather data (1991–2020) (Anonymous, 2024). Typically, 50–60% of the annual precipitation occurs during the primary growing season (May to September). However, a seasonal shift in precipitation distribution during transitional months like spring and fall, higher frequency of extreme rainfall events, and longer intervals between rain events are more noticeable, leading to crop failure in recent years (Yang et al., 2019). The mean monthly maximum temperatures varied from 17 to 22 °C between May and September (Anonymous, 2024). The monthly distribution of precipitation and temperature during the growing seasons from 2013 to 2024 are presented in Figure 1.

2.2 Experimental design

The experiment was conducted in a split-plot design with four replicates. The main-plots were assigned to eight different cropping sequences, while the sub-plots nested within the main-plots received three different nitrogen (N) levels (0, 45, and 90 kg N ha^{-1}), randomly assigned during the establishment year. All sub-plots were 2.5 m in width and 8.0 m in length (20 m^2), and a 0.6 m buffer area was maintained between main plots. Nine species including the seed crops of two perennial forage legumes (alsike clover [*Trifolium hybridum* L.], and red clover [*Trifolium pratense* L.]), three perennial grasses (creeping red fescue [*Festuca rubra* L.], meadow bromegrass [*Bromus riparius* Rehm.], and timothy [*Phleum pratense* L.]), and four annual crops (canola [*Brassica napus* L.], wheat [*Triticum aestivum* L.], pea [*Pisum sativum* L.], and barley [*Hordeum vulgare* L.]) constituted different phases of eight different cropping sequence treatments. More detailed information concerning years and crops grown in each cropping sequence can be found in Table 1 and Supplementary Figure 1. Six of the eight cropping sequence treatments were diversified with perennial forage legumes and grasses to compare with annual-based traditional sequences (i.e. canola-wheat only or in combination with barley and/or pea). During the seeding of annual

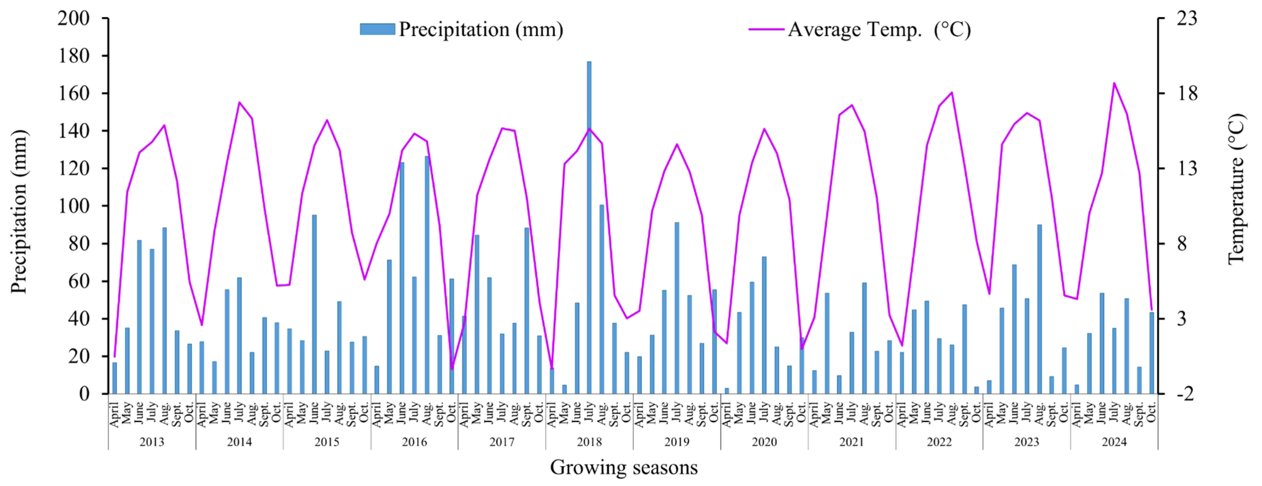

FIGURE 1
Growing season temperature and rainfall distribution from 2013 to 2024 at Beaverlodge Research Farm, Alberta. The weather date was summarized from historical data retrieved from the Department of Environment and Natural Resources, Government of Canada website (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html).

TABLE 1 Crop phases across eight different cropping sequences over the years of experimentation from 2013 to 2024.

Years	Cropping sequences and crops							
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
2013	Wheat	Pea	Canola	RC	AC	inRC	CRF	inAC
2014	Canola	Barely	Canola	RC	AC	RC	CRF	AC
2015	Wheat	Wheat	Canola	Wheat	Wheat	Wheat	CRF	Wheat
2016	Canola	Canola	Canola	Canola	Canola	Canola	Canola	Canola
2017	Wheat	Pea	Pea	RC/Wheat	AC/Wheat	RC/Wheat	Pea	AC/Wheat
2018	Canola	Wheat	MB	RC	AC	RC	CRF	AC
2019	Wheat	Canola	MB	Wheat	Wheat	Canola	CRF	CRF
2020	Canola	Pea	MB	Canola	Canola	Wheat	CRF	CRF
2021	FR	FR	FR	FR	FR	FR	FR	FR
2022	Wheat	Wheat	Pea	MB	Timothy	CRF	Pea	Canola
2023	Canola	Pea	RC/Wheat	MB	Timothy	CRF	AC/Wheat	Pea
2024	Wheat	Barley	Wheat	MB	Timothy	CRF	AC	Wheat

The cropping sequence treatments included S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. RC, Red clover; AC, Alsike clover; CRF, Creeping red fescue; MB, Meadow bromegrass; FR, Fall rye; inRC, Red clover inoculated with rhizobia; inAC, Alsike clover inoculated with rhizobia; '/' indicates intercropping.

crops, N fertilizer treatments were applied as band placement, while for perennial grasses, it was broadcast in the fall over the production years. All perennial forage seed crops underwent an initial establishment year characterized by vegetative growth, followed by one year of economic seed production for legumes and two years for grasses.

2.3 Agronomic management

The experiment was conducted under a no-tillage management system since its establishment in 2013. The test crops were seeded each year with a 2.4 m wide air seeder (Valmar Cross Slot IP Limited) with 30-cm row spacing (8 rows). Basal fertilizers for phosphorus (13.1 kg P ha^{-1}), potassium (16.6 kg K ha^{-1}), and sulfur (20 kg S ha^{-1}) were band-placed at sowing time. The broad-spectrum herbicides glyphosate (Roundup WeatherMAX, 3.2 L ha^{-1}) was applied twice, once in the fall and once in the spring, to effectively terminate perennial forage crops after their production years and to establish subsequent crops (Supplementary Table 1). Pests were monitored throughout the growing season; however, no infestations warranted the application of pesticides. The perennial crop residues were mowed post-harvest and uniformly distributed across the plot to maintain homogeneity and facilitate reproductive tiller production.

2.4 Data recording, yield sampling, processing, and analysis

The crops were sampled at physiological maturity from the middle two rows by taking 4 m row lengths from each treatment sub-plot for seed and aboveground biomass yield, and subsequent post-harvest analyses. The plant samples were air-dried to a constant weight to measure total aboveground biomass yields on an area basis. The samples were then threshed mechanically using an ALMACO LPR thresher (ALMACO Nevada, USA) to measure grain and straw yields.

A random sub-sample of cleaned seed and threshed straw from each sub-plot was ground using an electric grinder (Marathon Electric, Wausau, Wisconsin 54401, USA). Nitrogen concentration in the plant samples was determined using the dry combustion method described by Nelson and Sommers (1982). Briefly, 10–20 mg of ground plant materials were encapsulated in tin foils with 6 × 6 × 12 mm dimensions. The processed samples were then analyzed by a Vario EL Cube (Elementar Analysensysteme GmbH, Germany), where the combustion and reduction temperatures were maintained at 1150 °C and 850 °C, respectively. The tissue N concentration data were used to calculate N uptake and apparent fertilizer N recovery under experimental management conditions (see below).

2.5 Computation of canola equivalent yield

For uniform comparison among the sequences, the annual and perennial forage crop seed yield was expressed as Canola Equivalent Yield (CEY) in kg ha^{-1}. The CEY was calculated using the following formula (Liu et al., 2019; Khanal et al., 2021).

$$CEY\ (kg\ ha^{-1}) = seed\ \ yield\ \ of\ \ noncanola\ \ crop\ \ (kg\ ha) \times \frac{price\ of\ noncanola\ crop\ (\$\ kg^{-1})}{price\ of\ canola\ \ crop\ (\$\ kg^{-1})}$$

The prices of both canola and non-canola seeds were obtained from Agriculture Financial Services Corporation (Agriculture Financial Services Corporation, 2024). The seed commodity prices varied every month, and the yearly average price was used in the calculation (Supplementary Table 1). The cumulative CEY for each treatment subplot was calculated by summing the CEY of individual crops grown under the cropping system.

2.6 Computation of gross revenues and gross margins

Gross revenues were calculated based on the seed yields of all crops grown in each treatment sequence from 2013 to 2024. For each crop year, seed yields were multiplied by the annual average sale prices of seeds of the respective crops, which were summed over the years to obtain the total cumulative gross revenues. Gross margins were calculated as the difference between total revenue and variable costs across treatment sub-plots, including seed and seeding, fertilizer and fertilizer application, herbicide and herbicide application, mowing, harvesting, and storage. The variable inputs and operational costs were valued in Canadian Dollars ($CDN) and calculated for each treatment by adding all expenses on a per-hectare basis using the current price ($ ha^{-1}) (Supplementary Table 2). Other costs, such as equipment repairs, depreciation, land rent, common operating costs, insurance and property taxes, were not considered for the analyses as they did not vary across cropping sequences.

This study focused exclusively on seed yield as the measure of crop productivity and did not include forage biomass as an economic output. While this may appear to limit a complete assessment of overall crop output, the decision aligns with the research objective centered on seed production. The study location, a region recognized as a major exporter of forage seed, has limited demand for hay or biomass use, making seed yield the most relevant and economically significant metric. The CEYs, gross revenues, and gross margins were calculated based on the average annual prices of variable inputs and outputs; therefore, they do not account for how the profitability of crop sequences may vary under price elasticity.

2.7 Nitrogen use efficiency of the cropping system

For uniform comparison among the cropping sequences, NUE was calculated in terms of aboveground biomass yield and agronomic NUE for CEY. Accordingly, the aboveground biomass and the agronomic NUE for CEY were calculated using the following formula described by Khanal et al. (2021), which represents the amount of additional aboveground biomass and CEY seed harvested per kilogram of N fertilizer applied.

$$\text{Aboveground } \mathit{biomass\ \ NUE}\ \ (kg\ \ kg^{-1})$$

$$= \frac{Biomass\ \ yield\ \ at\ \ Nk - Biomass\ \ yield\ \ at\ \ N0}{Nk}$$

$$Agronomic\ \ NUE\ \ for\ \ CEY\ \ (kg\ \ kg^{-1})$$

$$= \frac{CEY\ \ at\ \ Nk - CEY\ \ at\ \ N0}{Nk}$$

Where *CEY* is Canola Equivalent Yield, *Nk* is the applied N rate (45 or 90 kg ha^{-1}, and N0 is without N.

2.8 Nitrogen uptake and apparent fertilizer N recovery

The N-uptake (kg ha^{-1}) by the crops grown in 2023 and 2024 was calculated by multiplying the dried sample biomass (straw and grain) by the corresponding N concentration. To examine apparent fertilizer N recovery, N uptake in non-nitrogen fertilized plot was subtracted from the N uptake in a plot at given nitrogen fertilizer rate and then divided by the corresponding fertilizer rate (Nk) (Craswell and Godwin, 1984), as shown in the equations below:

$$\text{Nitrogen Uptake } (Nup;\ kg\ \ ha^{-1}) =$$

$$\text{Tissue N concentration } \times \text{ Aboveground biomass}$$

where tissue N concentration and aboveground biomass were expressed in percentage and kg ha^{-1}, respectively.

$$\text{Apparent fertilizer N recovery } (\,\%\,) = \frac{Nup\ k\ -\ Nup\ \ control}{Nk} \times 100$$

where *Nup k* is N uptake in a plot at given N fertilizer rate, *Nup control* is N uptake in non-N fertilized plot and *Nk* is the applied N rate (45 or 90 kg ha^{-1}).

2.9 Statistical analyses

All data analyses were performed using the SAS OnDemand for Academics (SAS Institute, Inc., Cary, NC) in compliance with the standard procedure of split-plot design. The assumptions of normality (PROC UNIVARIATE) and homogeneity of variances (Levene's test) were examined prior to analysis. Data transformations were not required to meet normality assumptions. The data were then analyzed using the PROC GLIMMIX procedure, and the Kenward-Roger approximation method was used to determine degrees of freedom for the treatment factors. Cropping sequences and N rates were treated as fixed effects, whereas blocks and their interactions with cropping sequences and N were considered random effects.

Mathematically, the analytical model is expressed as:

$$Y_{ij} = \mu + B_i + S_j + (BS_{ij}) + N_k + (SN)_{jk} + \varepsilon_{ijk}$$

Indices:

Blocks: $i = 1,\ldots, r$

Cropping sequences (whole-plot levels): $j = 1,\ldots, a$

Nitrogen: $k = 1,\ldots, n$

Effects:

Fixed: μ (overall mean), S_j (cropping sequence), N_k (nitrogen), $(SN)_{jk}$ (interaction)

Random: $B_i \sim \mathcal{N}(0, \sigma^{2B})$ (Block), $BS_{ij} \sim \mathcal{N}(0, \sigma^{2BC})$, (whole plot error: block x cropping sequence), $\varepsilon_{ijk} \sim \mathcal{N}(0, \sigma^2)$ (sub-plot residual)

Error strata and tests:

Cropping sequence (c): test S_j against the whole-plot error (BS_{ij}).

Nitrogen (N): test N_k against the sub-plot residual ε_{ijk},

Interaction (S x N): test $(SN)_{jk}$ against the sub-plot residual ε_{ijk}.

Wherever treatment differences were found, Tukey's Honestly Significant Difference (HSD) procedure was used to separate means at a 5% significance level.

3 Results and discussion

3.1 Cumulative CEY from 2013 to 2024

The cumulative CEY varied significantly for the interaction between cropping sequences and N treatments (P <.0001) over the production years 2013-2024 (Figure 2). The legume to vernalizing grass rotation (S_4), with intermittent reoccurrence of red clover leading to meadow bromegrass phases, resulted in higher CEY than other cropping sequences across three N levels. In this cropping sequence, red clover was grown biennially in two alternating phases for four years, and meadow bromegrass was grown for three consecutive years over the twelve-year production period. The highest CEY in this sequence was driven by the higher yield and premium price of meadow bromegrass seed in the production years of 2023 and 2024. The seed yield of meadow bromegrass was 2420 and 910 kg ha^{-1} in 2023 and 2024, respectively, which was significantly higher than the average productivity of meadow bromegrass in the Peace region of western Canada, as reported by Azooz and Johnson (2014). Moreover, the seed price of meadow bromegrass was nearly eight times higher than that of canola ($4.82

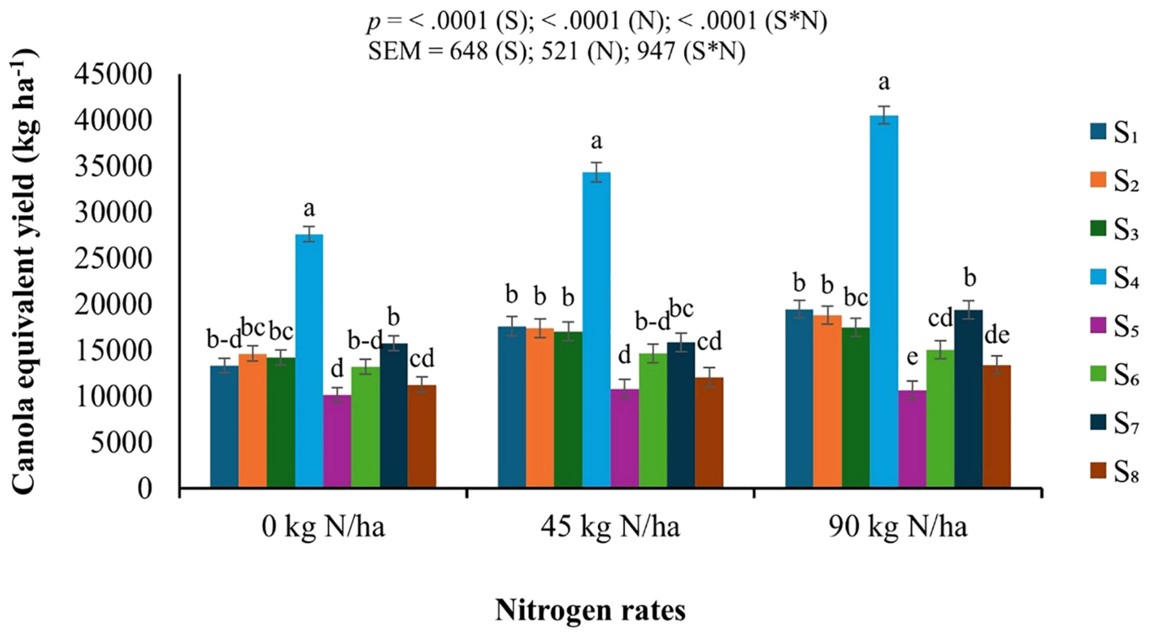

FIGURE 2
Cumulative canola equivalent yield of cropping sequences at three different nitrogen fertility levels at Beaverlodge Research Farm, Alberta, from 2013 to 2024. The cropping sequence treatments included: S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. The three nitrogen fertilizer rates were 0, 45, and 90 kg N ha^{-1} applied at the non-legume phase of cropping sequences. The crops grown in the cropping sequences included wheat, canola, pea, barley, meadow bromegrass, timothy, creeping red fescue, alsike clover, and red clover. Treatment columns followed by the same letter are not significantly different (p > 0.05). Error bars represent the Standard Error of the Mean (SEM). S, cropping sequences; N, nitrogen levels; S*N, interaction between cropping sequences and nitrogen levels.

vs. \$0.74 per kg in 2023 and \$4.79 *vs*. \$0.59 per kg in 2024) in those years (Agriculture Financial Services Corporation, 2023, 2024).

Notably, the seed price of perennial forages like meadow bromegrass increased substantially compared to canola in recent years. For example, the seed price of meadow bromegrass rose by 69% from \$2.83 per kg in 2018 to \$4.79 per kg in 2024. In contrast, the seed price of canola showed a modest increase of 28% from \$0.46 per kg in 2018 to \$0.59 per kg in 2024 (Agriculture Financial Services Corporation, 2018, 2024). The substantial price increase indicates an opportunity to leverage demand in emerging markets, which is a key consideration for crop planning (Edgerton, 2009). In contrast, lower CEY was recorded in the alsike clover (a perennial legume) to timothy (a non-vernalizing grass) rotation (S_5), irrespective of N fertility levels. The lower seed productivity of alsike clover (80 kg ha^{-1} in 2018) resulted in lower CEY in S_5. Our visual observations indicate that excessive moisture during alsike clover's flowering to maturity stages critically affected seed productivity in 2018. The physiological legacy of drier conditions in the preceding fall and winter could be the reason behind the shorter plants and smaller heads of timothy during the production periods of 2023 and 2024. Timothy displays reproductive asynchrony due to weather variability, resulting in reduced seed yield. Earlier in 2021, the Peace River region experienced a heatwave that significantly affected crop productivity, including timothy (Pandey, 2023). Garwood and Sinclair (1979) reported that timothy is sensitive to soil moisture deficit at the deeper soil horizons. The CEY of fescue-dominated sequence (S_7) was higher than that of the timothy- and clover-integrated cropping sequences, while remaining comparable to CEYs of annual crop-based sequences (S_1 and S_2). As fescue species are recognized for their eco-physiological benefits, such as improved soil structure, enhanced nutrient cycling, increased soil organic matter, and augmented water infiltration and retention (Hartwig and Ammon, 2002; Athar et al., 2022; Skersiene et al., 2023), their inclusion in crop diversification could be a sustainable approach for the study region.

3.2 Gross revenue of 12-year cropping sequences

The gross revenue was significantly influenced by cropping sequences (*P* <.0001), N rates (*P* = 0.005), and their interactions (*P* < 0.02) (Figure 3). The highest gross revenue was recorded from the legume to vernalizing grass rotation (S_4), with intermittent recurrence of red clover leading to meadow bromegrass phases, compared to annual-based and other diversified cropping sequences. As explained in the preceding sub-section, the economic advantage of this rotation was primarily influenced by crop prices and yields of different crops.

The higher seed price contributed to the significant increase in the gross revenue of legume-to-vernalizing grass rotation cropping sequence. Conversely, the cropping sequence with the lowest gross revenue was recorded from the legume-to-non-vernalizing grass

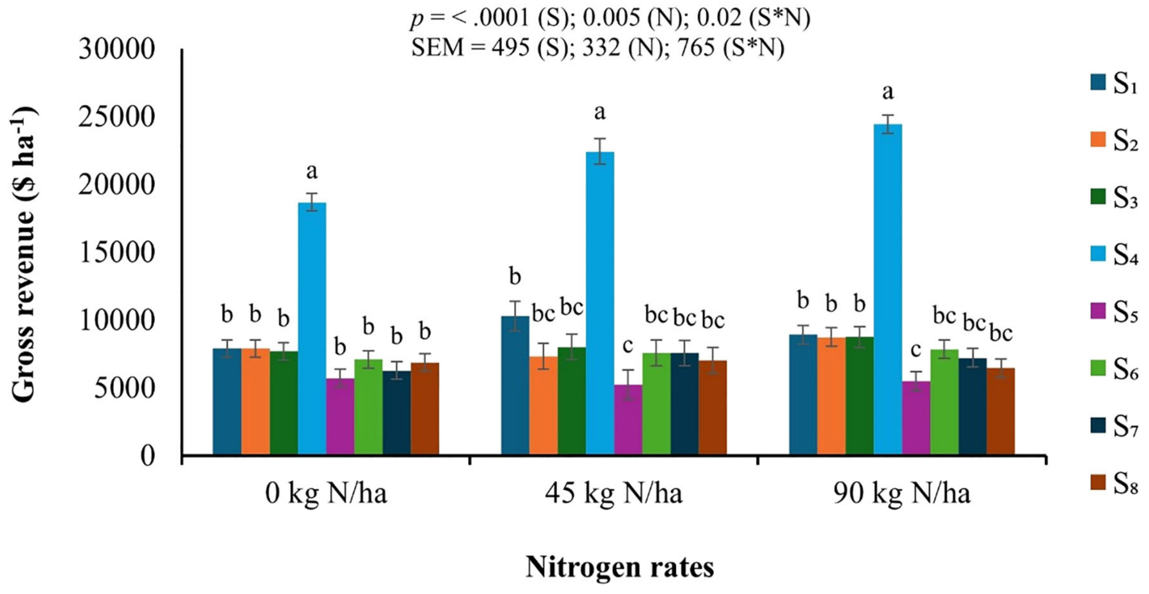

FIGURE 3
Cumulative gross revenue of cropping sequences at three different nitrogen fertility levels at Beaverlodge Research Farm, Alberta, from 2013 to 2024. The cropping sequence treatments included S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. The three nitrogen fertilizer rates were 0, 45, and 90 kg ha^{-1} applied at the non-legume phase of cropping sequences. The crops grown in the cropping sequences were wheat, canola, pea, barley, meadow bromegrass, timothy, creeping red fescue, alsike clover, and red clover. Treatment columns followed by the same letter are not significantly different (p > 0.05). Error bars represent the Standard error of the Mean (SEM). S, cropping sequences; N, nitrogen levels; S*N, interaction between S and N.

rotation (S_5), with intermittent recurrence of alsike clover leading to timothy phases, across all N fertility levels (Figure 3). This was primarily due to the lower productivity of both timothy and alsike clover during their production phases. The average seed yield of timothy was less than 200 kg ha^{-1}, while that of alsike clover was 80 kg ha^{-1}, both substantially lower than previously reported in the region (Yoder, 2004; John and Ogle, 2008).

Understanding crop adaptative behavior and economic dynamics is essential for developing resilient crop rotational strategies amid climate variability and shifting market conditions. Bansal et al. (2024) conducted a comparative analysis of diversified and conventional crop rotation systems in South Dakota, USA, and found that higher economic returns in diversified cropping systems are associated with increased crop yields. The crop-specific sensitivity to weather anomalies could have resulted in seasonal yield variability of crops in our study. The productivity gains typically increase expected revenue per unit area as they directly translate to higher output and potential income, but higher supply can also lower crop prices (Pouliot, 2019). Therefore, the commodity prices can be a key driver of on-farm profitability (Canales et al., 2021). The gross revenues of different forage-based sequences (S_6, S_7, and S_8) were comparable to those of annual cropping systems (S_1 and S_2), irrespective of different N application rates. This result suggests that well-managed perennial-integrated cropping systems can be viable alternatives to recurrent annual crop rotations enhancing the resilience of farm income.

3.3 Gross margin of 12-year cropping sequences

Gross margin is considered here as a primary indicator of the economic viability of diversified cropping systems, as it accounts for the differential costs across different cropping sequences. Overall, the highest gross margins were recorded from the legume (red clover) to vernalizing grass (meadow bromegrass) rotation (S_4) with an average of $21,143 ha^{-1}, and the lowest in the legume (alsike clover) to non-vernalizing grass (timothy) rotation (S_5) with an average of $1,688 ha^{-1} (Figure 4). The legume to vernalizing grass rotation (S_4) consistently exhibited a higher gross margin across all N rates. High yields and strong market prices for meadow bromegrass in 2023 and 2024 drove the profitability of the S_4 sequence, underscoring the importance of understanding crop adaptability and market signals.

Abundant literature substantiates the economic viability of diversified cropping systems. Sánchez et al. (2022) performed a meta-analysis of 119 peer-reviewed articles and found that diversified systems generate profits comparable to or greater than simplified farming systems. Alcon et al. (2024) studied the medium- and long-term economic performance of diversified cropping systems and found higher gross margins from diversification than monocrop farming practices. Although the magnitude of profit margins depends on crops, diversification can promote better financial outcomes by mitigating risks related to extreme weather,

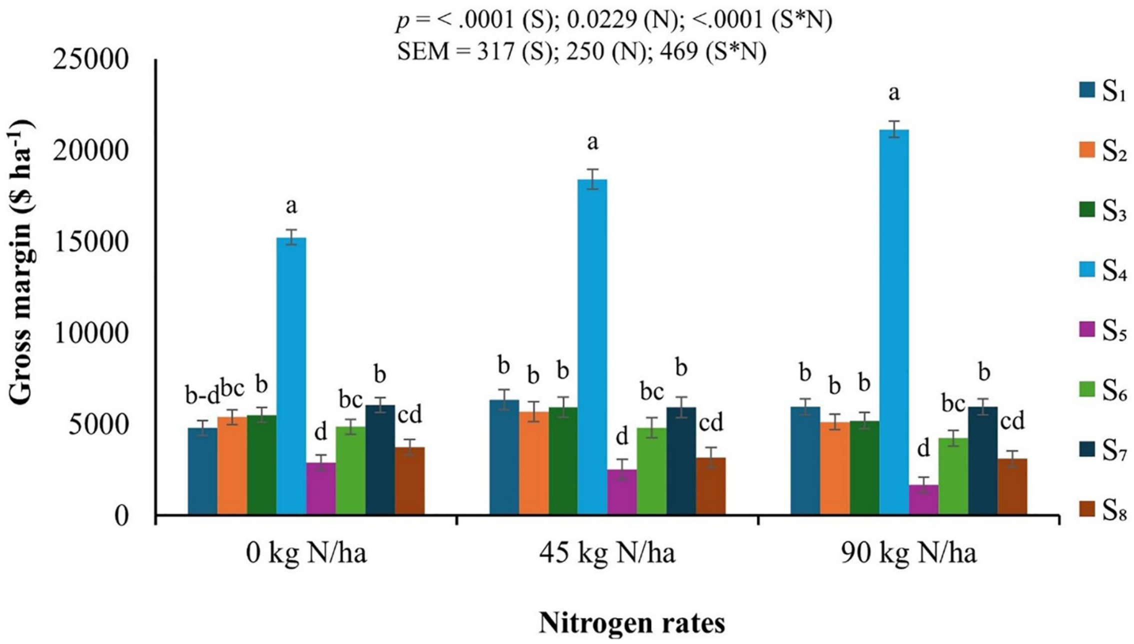

FIGURE 4
Cumulative gross margins under different cropping sequences and nitrogen fertility levels at Beaverlodge Research Farm, Alberta from 2013 to 2024. The cropping sequence treatments included S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. The three nitrogen fertilizer rates were 0, 45, and 90 kg ha^{-1} applied at the non-legume phase of cropping sequences. The crops grown in the cropping sequences were wheat, canola, pea, barley, meadow bromegrass, timothy, creeping red fescue, alsike clover, and red clover. Treatment columns followed by the same letter are not significantly different ($p > 0.05$). Error bars represent the standard error of the mean (SEM). S, cropping sequences; N, nitrogen levels; S*N, interaction between S and N.

pest outbreaks, yield loss, and price volatility (Gaudin et al., 2015; Mortensen and Smith, 2020; Khanal et al., 2021; Mihrete and Mihretu, 2025). The thoughtful selection of crops with complementary growth characteristics and resource requirements can enhance profit margins by reducing input costs (Khanal et al., 2021; Mihrete and Mihretu, 2025). Overall, strategic crop planning can enhance efficiency, reduce input costs, and improve profit margins in diversified farming systems.

Farm profitability is driven by both higher yields and cost savings from reducing or appropriately substituting inputs such as fertilizers and pesticide costs. Higher crop yields achieved through excessive use of inputs beyond optimal levels can lead to diminishing returns, where additional inputs do not proportionally increase yields but raise costs (Reader et al., 2018; Pittman, 2020; Liang, 2023). As expected, we observed a significant improvement in gross margin with the increase of N rates from 0 to 45 kg N ha^{-1} for most of the diversified treatment sequences. However, a further increase to 90 kg N ha^{-1} did not yield significant economic benefits. These findings highlight the potential to fine-tune N management in cropping systems that include annual or perennial legumes. Analyzing over 34 years of experimental results in the USA, Breza et al. (2023) concluded that cropping systems complexity enhanced organic nutrient recycling, but N fertilization counteracted the beneficial effects of crop diversification. Moreover, the excess N may trigger environmental issues like nitrate leaching (De Laporte et al., 2021), leading to soil degradation (Awadelkareem et al., 2023), water pollution (Akinnawo, 2023), and increased greenhouse gas emissions (Menegat et al., 2022) and impairment of beneficial soil microbiome functionality (Beltran-Garcia et al., 2021). Therefore, rational N fertilization is essential to improve productivity and reduce environmental footprint of diversified cropping systems.

3.4 Cumulative aboveground biomass yield from 2013 to 2024

During 2013–2024, the effects of cropping sequences (P <.0001), N rates (P <.0001), and their interaction (P = 0.0002) were significant for cumulative aboveground biomass yield (Figure 5). The conventional and diversified annual cropping systems (S_1 and S_2) consistently produced higher aboveground biomass yields across the N application rates compared with forage-based sequences (S_3 to S_8). Among perennial forage-based systems (S_3 to S_8), the legume-to-vernalizing grass rotation (S_4) resulted in the highest aboveground biomass yield, whereas the turf grass-to-legume rotation (S_7) had the lowest aboveground biomass yield across all N rates. High aboveground biomass yield in the cropping sequence with intermittent inclusion of red clover (legume) and meadow bromegrass (vernalizing grass) was concurrent with an exceptionally high seed yield of meadow bromegrass under favorable weather and crop-growing conditions in 2023 and 2024. In contrast, the lower aboveground biomass yield of creeping red

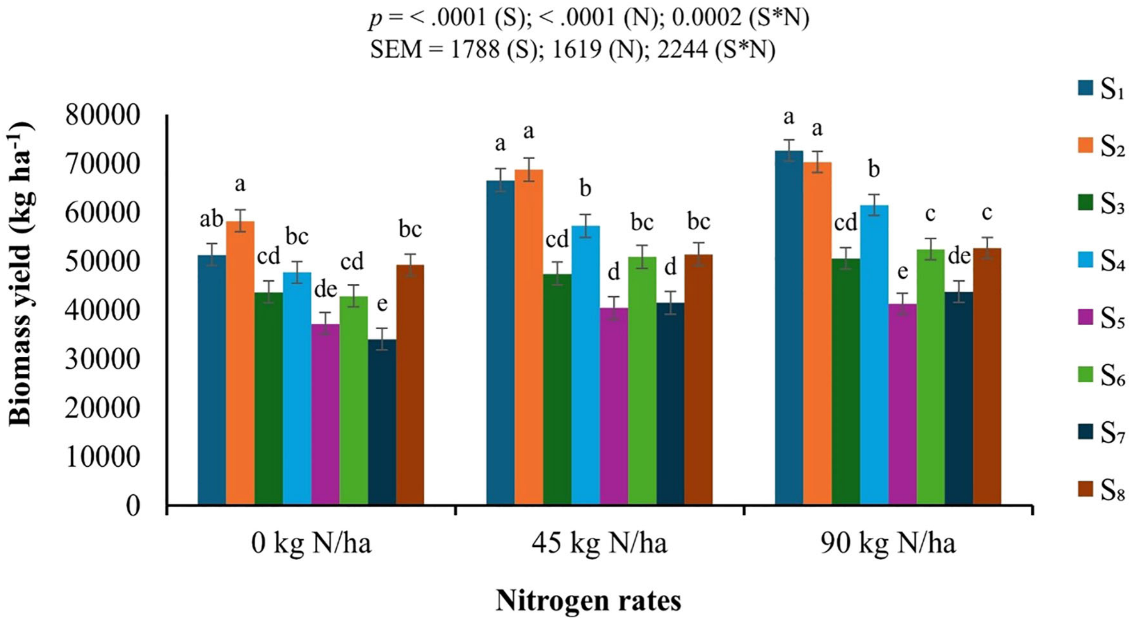

FIGURE 5
Cumulative biomass yield under different cropping sequences and nitrogen fertility level at Beaverlodge Research Farm, Alberta, from 2013 to 2024. The cropping sequence treatments included S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. The three nitrogen fertilizer rates were 0, 45, and 90 kg ha^{-1} applied at the non-legume phase of cropping sequences. The crops grown in the cropping sequences were wheat, canola, pea, barley, meadow bromegrass, timothy, creeping red fescue, alsike clover, and red clover. Treatment columns followed by the same letter are not significantly different (p > 0.05). Error bars represent the Standard error of the Mean (SEM). S, cropping sequences; N, nitrogen levels; S*N, interaction between S and N.

fescue led to reduced overall aboveground biomass productivity in the turfgrass-to-legume rotation (S$_7$) across all N rates. It is well established that perennial grasses have high root-to-shoot ratios because of their extensive, deep root systems and contribute to soil health and other ecosystem services (Beard, 1973; Bolinder et al., 2002; Thiagarajan et al., 2018). The perennial growth habit, characterized by greater allocation to belowground biomass can enhance carbon sequestration and help mitigate climate change risks (Franzluebbers et al., 2014; Ojija, 2024; Skersiene et al., 2024).

Enhanced aboveground biomass productivity in annual cropping systems is primarily attributed to their higher responses to N fertilization (Larsen et al., 2024). This responsiveness is due to their efficient uptake and utilization of available N, leading to accelerated growth rates and higher yields (Omara et al., 2019; Liu Z. et al., 2022; Wen et al., 2023). In contrast, forage-based sequences with perennial grasses and legumes often exhibit slower initial growth and allocate a larger proportion of resources to root development, which can result in slower aboveground growth compared with annual-based sequences (Bolinder et al., 2002; Hakala et al., 2009; Thiagarajan et al., 2018; Vico and Brunsell, 2018). It is also noteworthy that aboveground biomass yield measurements of perennials were only performed during the seed production phases (one year after crop establishment), because the plant growth in both perennial forage and seed production systems is insufficient to justify harvesting during the establishment year in this region. The exclusion of perennial biomass in the establishment year partly contributed to lower aboveground biomass yields observed in perennial forage-based diversified sequences. We also observed that aboveground biomass yield increased substantially with the application of 45 kg N ha^{-1}, and no further yield improvement was realized at higher N level (90 kg N ha^{-1}). The perennial crops, therefore, contribute to sustainable agroecosystems because of lower N demand and greater belowground biomass inputs.

TABLE 2 Agronomic and aboveground biomass nitrogen use efficiencies (NUE) of different cropping sequences from 2013 to 2024.

Cropping sequences	Agronomic NUE (kg kg^{-1})*		Aboveground biomass NUE (kg kg^{-1})	
	45 kg N ha^{-1}	90 kg N ha^{-1}	45 kg N ha^{-1}	90 kg N ha^{-1}
S$_1$	94.8ab	68.2b	339a	237a
S$_2$	60.9bc	46.3bc	233ab	134bc
S$_3$	63.0a-c	36.2bc	83b-d	76b-d
S$_4$	115a	121a	211a-c	153ab
S$_5$	14.6c	13.2c	71cd	45cd
S$_6$	32.2c	20.4c	178b-d	107b-d
S$_7$	66.2a-c	73.3b	165b-d	108b-d
S$_8$	18.2c	24.0c	48d	39d
p-values	<.0001	<.0001	<.0001	<.0001
SEM	10.78	8.840	34.48	20.06

The cropping sequence treatments included S$_1$ = Conventional annual rotation; S$_2$ = Diversified annual rotation; S$_3$ = Annual to perennial rotation; S$_4$ = Legume to vernalizing grass; S$_5$ = Legume to non-vernalizing grass; S$_6$ = Legume to turf grass; S$_7$ = Turf grass to legume; and S$_8$ = Diversified perennial to annual. *= Agronomic NUE was calculated based on the cumulative CEY. SEM= Standard error of mean (n=4). Numbers followed by different letters are significantly different at $p < 0.05$ according to Tukey's test.

3.5 Nitrogen use efficiency

The mean NUE indices for the cropping sequence treatments from 2013 to 2024 are summarized in Table 2. The highest agronomic NUE was observed in the perennial legume-to-vernalizing grass rotation (S$_4$) at both N application rates of 45 and 90 kg N ha^{-1}, followed by the conventional annual rotation (S$_1$) at 45 kg N ha^{-1}. While annual crops generally exhibited higher agronomic NUE than perennials, the yield-specific N efficiency (measured as CEY-based agronomic NUE) can be higher in perennial forage-based sequences (Weih et al., 2011; Khanal et al., 2021). The higher agronomic NUE in the perennial legume-to-vernalizing grass cropping sequence, mainly due to the higher seed production of meadow bromegrass in 2023 and 2024, showed greater efficiency in converting applied N into grain yield through improved uptake and assimilation (Fageria and Baligar, 2005; Govindasamy et al., 2023). In contrast, cropping sequences S$_5$, S$_6$, and S$_8$ exhibited the lowest agronomic NUE across both N application rates. The magnitude of variation in agronomic NUE among cropping sequences is largely influenced by the seed yields of different crops, which vary considerably among crop species. Numerous studies have substantiated that agronomic N use efficiency was influenced by crop types and varieties, growth characteristics, growing-season weather, and agronomic management practices (Ivić et al., 2021; Khanal et al., 2021; Govindasamy et al., 2023).

Similar to agronomic NUE, aboveground biomass NUE varied greatly across cropping sequence treatments (Table 2). The highest aboveground biomass NUE was observed in conventional annual rotation (S$_1$) at both N levels, indicating a strong ability to utilize soil-applied N for aboveground biomass and grain production. Annual crops often exhibit higher aboveground biomass NUE than perennials because of their rapid growth rates, shorter life cycles, and intensive nutrient uptake patterns (Weih et al., 2018). Annual crops usually allocate more resources to aboveground biomass and seed production, whereas perennial grasses tend to allocate more resources to root development (Tilman et al., 2006; Means et al., 2022). These differences explain why annual crops display higher aboveground biomass NUE than perennials. Previous studies suggest that annual crops depend heavily on external fertilizer inputs, whereas perennials rely on vigorous root systems and microbial symbiosis for nutrient retention and recycling (Mueller et al., 2012).

3.6 Tissue N concentration, N uptake, and apparent recovery of applied N of various crops under different N fertilization

The N concentration and uptake by straw and grain were influenced by treatment interactions, as shown in Tables 3 and 4. As anticipated, higher N concentrations were recorded in the plant tissues of legume species compared with annual cereals and perennial grasses in both 2023 and 2024. Previous research reported that

TABLE 3 Tissue nitrogen concentration, nitrogen uptake, and apparent recovery of applied nitrogen (ANR) of various crops under different nitrogen levels during their production phase in 2023.

Cropping sequences	Crops	Concentration (%)						Uptake 9kg N ha^{-1}						ANR (%)	
		Straw			Grain			Straw			Grain				
		———————N rates (kg ha^{-1}) ———————													
		0	45	90	0	45	90	0	45	90	0	45	90	45	90
S_1	C	0.39	0.37	0.46	2.73e-h	3.00c-f	3.40a-d	14.7	21.9	28.6	40.1fg	74.6c-f	101a-c	158a	83.1b-d
S_2	P	1.22	1.59	1.19	2.98d-g	3.16b-f	3.39a-d	47.2	62.3	50.0	59.1ef	66.4d-f	69.9c-f	49.7b-e	15.2e
S_3	W	0.30	0.41	0.51	1.69k	2.25h-j	2.73e-h	8.9	14.5	17.5	56.6e-h	94.5a-d	117a	96.7ab	85.9bc
S_4	MB	0.36	0.51	0.59	2.29h-j	2.56g-i	2.71f-h	13.9	13.9	18.0	51.9ef	65.4d-f	66.7d-f	29.9c-e	21.1de
S_5	T	0.88	0.96	1.06	3.25b-e	3.43a-d	3.52a-d	10.0	16.2	13.8	5.65h	5.41h	5.19h	13.2e	3.71e
S_6	CRF	0.87	0.99	1.05	2.61gh	2.75e-h	2.83e-g	11.6	11.8	15.1	16.7gh	18.6gh	18.4h-k	4.72e	5.66de
S_7	W	0.30	0.37	0.51	2.03i-k	1.85jk	2.63f-h	10.1	16.1	20.9	77. 5c-e	82.2b-e	113ab	23.9c-e	52.6b-e
S_8	P	1.37	1.33	1.54	3.52a-c	3.92a	3.63ab	42.8	46.9	60.7	53.4ef	52.8ef	56.4ef	7.76e	23.1de
p-values		0.221			<.0001			0.360			<.0001			0.009	
SEM		0.086			0.101			4.195			6.362			13.12	

The cropping sequence treatments included S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. The nitrogen rates included 0, 45, and 90 kg N ha^{-1} applied at the non-legume phase of cropping sequences. SEM = Standard error of mean (n=4). Numbers followed by different letters are significantly different at $p < 0.05$ according to Tukey's test. C, canola; CRF, creeping red fescue; MB, meadow bromegrass; P, peas; T, timothy; W, wheat.

TABLE 4 Tissue nitrogen concentration, nitrogen uptake, and apparent recovery of applied nitrogen (ANR) of various crops under different nitrogen levels during their production phase in 2024.

Cropping sequences	Crops	Concentration (%)						Uptake 9kg N ha^{-1}						ANR (%)	
		Straw			Grain			Straw			Grain				
		———————N rates (kg ha^{-1}) ———————													
		0	45	90	0	45	90	0	45	90	0	45	90	45	90
S_1	W	0.29	0.39	0.50	1.68hi	2.14f-i	2.56e-g	5.53	10.1	11.2	34.0ef	62.0bc	62.3bc	57.1a	37.7ab
S_2	B	0.41	0.57	0.81	1.60i	1.98g-i	2.23f-i	10.3	15.8	21.9	54.8cd	70.4a-c	75.8ab	21.2a-d	36.3ab
S_3	RC	1.18	1.18	1.29	6.21a	5.99ab	5.93ab	32.4	27.6	29.4	8.78g	8.73g	5.75g	-10.6d	-6.59d
S_4	MB	0.45	0.41	0.52	1.97g-i	2.03g-i	2.51e-g	4.95	7.45	17.2	8.35g	16.2fg	38.4de	22.9a-d	46.9a
S_5	T	0.64	0.74	0.79	3.07c-e	3.28cd	3.64c	7.83	8.33	7.54	6.18g	8.20fg	4.65g	7.6b-d	-2.01d
S_6	CRF	0.62	0.97	1.04	2.29f-h	2.13f-i	2.28f-h	8.40	15.6	18.2	8.10g	11.6g	11.1g	23.8a-d	14.2a-d
S_7	AC	1.14	1.18	1.29	5.49b	5.87ab	5.77ab	13.4	16.7	18.1	8.18g	2.90g	3.23g	-4.23d	-0.21cd
S_8	W	0.38	0.43	0.52	2.39fg	2.50e-g	2.75d-f	7.98	11.9	14.6	62.4bc	79.9ab	86.3a	49.4a	33.8a-c
p-values		0.425			0.003			0.108			<.0001			0.049	
SEM		0.075			0.126			2.369			3.853			8.263	

The cropping sequence treatments included S_1 = Conventional annual rotation; S_2 = Diversified annual rotation; S_3 = Annual to perennial rotation; S_4 = Legume to vernalizing grass; S_5 = Legume to non-vernalizing grass; S_6 = Legume to turf grass; S_7 = Turf grass to legume; and S_8 = Diversified perennial to annual. The nitrogen rates included 0, 45, and 90 kg N ha^{-1} applied at the non-legume phase of cropping sequences. SEM = Standard error of mean (n=4). Numbers followed by different letters are significantly different at $p < 0.05$ according to Tukey's test. AC, alsike clover; B, barley; CRF, creeping red fescue; MB, meadow bromegrass; T, timothy; RC, red clover; W, wheat.

legumes have evolved mechanisms to maintain a high N concentration in both shoots and seeds (McKey, 1994; Schenk et al., 1995). Naturally, the N-fixing symbiosis with rhizobia contributes to the accumulation of more N and the maintenance of elevated tissue N concentrations in legume plants (Zahran, 1999). However, despite this higher N concentration, legumes often exhibit lower rates of photosynthesis and plant growth per unit of N in the plant relative to cereals (Evans, 1989; Del Pozo et al., 2000). Conversely, cereals typically have a more efficient use of N in photosynthesis, as they invest more N into photosynthetic enzymes like Ribulose-1,5-bisphosphate carboxylase/oxygenase (RUBISCO) and have higher rates of C assimilation per unit of leaf tissue N (Makino, 2011).

While tissue N concentration increased with higher N rates, N uptake varied significantly among cropping sequence treatments because of differences in crop species. The observed variations in straw and grain N uptake were attributed to differences in aboveground biomass production among crops grown under the tested treatment sequences (Figure 5, Tables 3, 4). For example, thegrain N concentration of alsike clover was highest in 2024, but the uptake was among the lowest due to low seed yield. Conversely, the highest grain N uptake was recorded in wheat during 2023 and 2024, which was attributed to its higher seed yield compared to other test crops. With an external N supply, annual crops often achieve greater biomass accumulation and higher yields compared to perennials under similar environmental conditions (Fageria and Baligar, 2005; Govindasamy et al., 2023). The results suggest that annual grain crops tend to have greater total N uptake, likely due to their ability to utilize available N efficiently (Guinet et al., 2020). A similar result was observed in ANR, as annual crops recorded the highest recovery and demonstrated superior fertilizer N uptake. Unlike cereals, perennial legumes are less responsive to applied N fertilizers since they meet their N requirements mostly through symbiotic N fixation (Šidlauskaitė and Kadžiulienė, 2023; Tang et al., 2024). Furthermore, the ANR calculation considered only the fertilizer-derived N uptake, excluding any contribution of atmospheric N_2 fixation, which was not estimated in this study. The capacity of legumes for N-fixation can make their uptake of fertilizer N less responsive, resulting in a lower or negative N recovery. Similarly, legumes can leave more N in the soil than is removed by uptake, resulting in negative ANR values (Guinet et al., 2020). Excessive N application to legumes can even suppress root nodulation and N fixation (Sharma and Bali, 2017), suggesting a complex interaction of ecophysiological feedback mechanisms.

4 Conclusion

This long-term study elucidated that strategic integration of perennial forage seed crops in the annual rotations can enhance agronomic productivity, nitrogen use efficiency, and economic returns, thereby strengthening resilience of the production systems. Profitability was shaped by crop species with strong agroclimatic adaptation and favorable market prices, as evidenced by the intermittent inclusion of red clover and meadow bromegrass. Nitrogen application at 45 kg N ha^{-1} optimized economic benefits across cropping sequences, while higher rates (90 kg N ha^{-1}) yielded diminishing returns, highlighting opportunities to rationalize N management. To further inform cropping sequence design, future studies should investigate allelopathic effects and facilitatory interactions among crop species.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KB: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. NK: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. MT: Supervision, Validation, Visualization, Writing – review & editing. NL: Funding acquisition, Methodology, Writing – review & editing. NR: Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing. JO: Funding acquisition, Methodology, Writing – review & editing. BS: Funding acquisition, Methodology, Writing – review & editing. RL: Funding acquisition, Methodology, Writing – review & editing. RK: Funding acquisition, Methodology, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. Funding was provided jointly by Agriculture and Agri-Food Canada (AAFC) and the Peace Region Forage Seed Association (PRFSA) in the initial phase (2013 to 2017; Project J-000652) and subsequently by AAFC from 2018 to 2026 (Projects J-001772, and J-002685).

Acknowledgments

This article is based on the Master of Science thesis of Keshav Bhattarai, submitted in partial fulfillment of the requirements for the degree in Plant Science at University of Alberta. The funding jointly provided by Agriculture and Agri-Food Canada (AAFC) and the Peace Region Forage Seed Association (PRFSA) in the initial phase (2013 to 2017; Project J-000652) and subsequently by AAFC from 2018 to 2026 (Projects J-001772 and J-002685), was instrumental in enabling the long-term field experimentation and analysis presented in the study. The authors gratefully acknowledge Henry Klein-Gebbinck, Sarah Kuzmicz, Rahman Azooz, Pat Gansevles, Andrea Brown and numerous seasonal students and temporary staff for their expertise and technical supports. Special thanks are extended to Calvin Yoder and Talon Gauthier for their cooperation and partnership.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Co-pilot was used for correcting English grammar.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1732922/full#supplementary-material

References

Acton, D. F., and Gregorich, L. J. (1995). *The health of our soils: toward sustainable agriculture in Canada* (Ottawa, ON: Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada).

Agriculture Financial Services Corporation (2018). *AgriStability price lists*. Available online at: https://afsc.ca/income-stabilization/agristability/agristability-price-lists/ (Accessed April 8, 2025).

Agriculture Financial Services Corporation (2023). *AgriStability price lists*. Available online at: https://afsc.ca/income-stabilization/agristability/agristability-price-lists/ (Accessed April 8, 2025).

Agriculture Financial Services Corporation (2024). *AgriStability price lists*. Available online at: https://afsc.ca/income-stabilization/agristability/pricing/ (Accessed April 8, 2025).

Akinnawo, S. O. (2023). Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. *Environ. Chall.* 12, 100733. doi: 10.1016/j.envc.2023.100733

Alcon, F., Albaladejo-García, J. A., Martínez-García, V., Rossi, E. S., Blasi, E., Lehtonen, H., et al. (2024). Cost benefit analysis of diversified farming systems across Europe: Incorporating non-market benefits of ecosystem services. *Sci. Total Environ.* 912, 169272. doi: 10.1016/j.scitotenv.2023.169272

Anonymous (2024). "Canadian climate normal 1991–2020 station data," in *Climate Normals and Averages, Past weather and climate* (Government of Canada). Available online at: https://climate.weather.gc.ca/climate_normals/results_1991_2020_e.html?searchType=stnProv&lstProvince=AB&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=290000000&dispBack=0.

Athar, T., Fatima, H., Khan, M. K., Pandey, A., Shahid, S., Hamurcu, M., et al. (2022). "Potential role of turfgrasses and understorey vegetation for mitigating the changing climate," in *Climate Change Alleviation for Sustainable Progression* (CRC Press, Boca Raton, FL), 347–367.

Awadelkareem, W., Haroun, M., Wang, J., and Qian, X. (2023). Nitrogen interactions cause soil degradation in greenhouses: Their relationship to soil preservation in China. *Horticulturae* 9, 340. doi: 10.3390/horticulturae9030340

Azooz, R., and Johnson, T. (2014). *Seed yield of bromegrass varieties grown in the Peace*. Available online at: http://www.peaceforageseed.ca/pdf/The%20Seed%20Head%20Factsheet%205%20Bromegrass%20Yields%20in%20the%20Peace%20final.pdf (Accessed March 7, 2025).

Bansal, S., Wang, T., and Osborne, S. L. (2024). Yield and profit comparison of diversified versus conventional crop rotation systems in South Dakota. *Agron. J.* 116, 3145–3157. doi: 10.1002/agj2.21688

Beard, J. B. (1973). *Turfgrass: science and culture* (Englewood Cliffs, NJ: Prentice-Hall).

Beltran-Garcia, M. J., Martínez-Rodríguez, A., Olmos-Arriaga, I., Valdes-Salas, B., Di Mascio, P., and White, J. F. (2021). Nitrogen fertilization and stress factors drive shifts in microbial diversity in soils and plants. *Symbiosis* 84, 379–390. doi: 10.1007/s13199-021-00787-z

Bogužas, V., Skinulienė, L., Butkevičienė, L. M., Steponavičienė, V., Petrauskas, E., and Maršalkienė, N. (2022). The effect of monoculture, crop rotation combinations, and continuous bare fallow on soil CO2 emissions, earthworms, and productivity of winter rye after a 50-year period. *Plants* 11, 431. doi: 10.3390/plants11030431

Bolinder, M. A., Angers, D. A., Bélanger, G., Michaud, R., and Laverdière, M. R. (2002). Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. *Can. J. Plant Sci.* 82, 731–737. doi: 10.4141/P01-139

Bowles, T. M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M. A., Culman, S. W., et al. (2020). Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth* 2, 284–293. doi: 10.1016/j.oneear.2020.02.007

Brannan, T., Bickler, C., Hansson, H., Karley, A., Weih, M., and Manevska-Tasevska, G. (2023). Overcoming barriers to crop diversification uptake in Europe: a mini review. *Front. Sustain. Food Syst.* 7. doi: 10.3389/fsufs.2023.1107700

Breza, L. C., Mooshammer, M., Bowles, T. M., Jin, V. L., Schmer, M. R., Thompson, B., et al. (2023). Complex crop rotations improve organic nitrogen cycling. *Soil Biol. Biochem.* 177, 108911. doi: 10.1016/j.soilbio.2022.108911

Broersma, K., Robertson, J. A., and Chanasyk, D. S. (1997). The effects of diverse cropping systems on aggregation of a Luvisolic soil in the Peace River region. *Can. J. Soil Sci.* 77, 323–329. doi: 10.4141/S96-013

Brühl, C. A., and Zaller, J. G. (2021). "Indirect herbicide effects on biodiversity, ecosystem functions, and interactions with global changes," in *Herbicides*. Eds. R. Mesnage and J. G. Zaller (Elsevier, Amsterdam), 231–272. doi: 10.1016/B978-0-12-823674-1.00005-5

Brunharo, C. A., Gast, R., Kumar, V., Mallory-Smith, C. A., Tidemann, B. D., and Beckie, H. J. (2022). Western United States and Canada perspective: are herbicide-resistant crops the solution to herbicide-resistant weeds? *Weed Sci.* 70, 272–286. doi: 10.1017/wsc.2022.6

Campbell, B. M., Vermeulen, S. J., Aggarwal, P. K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A. M., et al. (2016). Reducing risks to food security from climate change. *Glob. Food Sec.* 11, 34–43. doi: 10.1016/j.gfs.2016.06.002

Canales, E., Bergtold, J. S., and Featherstone, A. (2021). Farm efficiency and productivity growth: The effect of commodity prices. *J. Appl. Farm Econ.* 4, 3. doi: 10.7771/2331-9151.1053

Cappelli, S. L., Domeignoz-Horta, L. A., Loaiza, V., and Laine, A. L. (2022). Plant biodiversity promotes sustainable agriculture directly and via belowground effects. *Trends Plant Sci.* 27, 674–687. doi: 10.1016/j.tplants.2022.02.003

Chahal, I., Hooker, D. C., Deen, B., Janovicek, K., and Van Eerd, L. L. (2021). Long-term effects of crop rotation, tillage, and fertilizer nitrogen on soil health indicators and crop productivity in a temperate climate. *Soil Tillage Res.* 213, 105121. doi: 10.1016/j.still.2021.105121

Craswell, E. T., and Godwin, D. C. (1984). The efficiency of nitrogen fertilizers applied to cereals grown in different climates. *Adv. Plant Nutr.* 1, 1–55.

De Laporte, A., Banger, K., Weersink, A., Wagner-Riddle, C., Grant, B., and Smith, W. (2021). Economic and environmental nitrate leaching consequences of 4R nitrogen management practices including use of inhibitors for corn production in Ontario. *J. Environ. Manage.* 300, 113739. doi: 10.1016/j.jenvman.2021.113739

Del Pozo, A., Garnier, E., and Aronson, J. (2000). Contrasted nitrogen utilization in annual C3 grass and legume crops: physiological explorations and ecological considerations. *Acta Oecol.* 21, 79–89. doi: 10.1016/S1146-609X(00)00113-2

Edgerton, M. D. (2009). Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiol.* 149, 7–13. doi: 10.1104/pp.108.130195

Evans, J. R. (1989). Photosynthesis and nitrogen relationships in leaves of C3 plants. *Oecologia* 78, 9–19. doi: 10.1007/BF00377192

Fageria, N. K., and Baligar, V. C. (2005). Enhancing nitrogen use efficiency in crop plants. *Adv. Agron.* 88, 97–185. doi: 10.1016/S0065-2113(05)88004-6

Fletcher, A. J., Hurlbert, M., Hage, S., and Sauchyn, D. (2021). Agricultural producers' views of climate change in the Canadian prairies: implications for adaptation and environmental practices. *Soc Nat. Resour.* 34, 331–351. doi: 10.1080/08941920.2020.1823541

Franzluebbers, A. J., Sawchik, J., and Taboada, M. A. (2014). Agronomic and environmental impacts of pasture–crop rotations in temperate North and South America. *Agric. Ecosyst. Environ.* 190, 18–26. doi: 10.1016/j.agee.2013.09.017

Garwood, E. A., and Sinclair, J. (1979). Use of water by six grass species. 2. Root distribution and use of soil water. *J. Agric. Sci.* 93, 25–35. doi: 10.1017/S0021859600086081

Gaudin, A. C., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., et al. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PloS One* 10, e0113261. doi: 10.1371/journal.pone.0113261

Govindasamy, P., Muthusamy, S. K., Bagavathiannan, M., Mowrer, J., Jagannadham, P. T. K., Maity, A., et al. (2023). Nitrogen use efficiency—a key to enhance crop productivity under a changing climate. *Front. Plant Sci.* 14. doi: 10.3389/fpls.2023.1121073

Guinet, M., Nicolardot, B., and Voisin, A. S. (2020). Provision of contrasted nitrogen-related ecosystem services among grain legumes. *Agron. Sustain. Dev.* 40, 33. doi: 10.1007/s13593-020-00637-0

Hakala, K., Keskitalo, M., Eriksson, C., and Pitkänen, T. (2009). Nutrient uptake and biomass accumulation for eleven different field crops. *Agric. Food Sci.* 18, 366–387. doi: 10.23986/afsci.5947

Harkness, C., Areal, F. J., Semenov, M. A., Senapati, N., Shield, I. F., and Bishop, J. (2021). Stability of farm income: The role of agricultural diversity and agri-environment scheme payments. *Agric. Syst.* 187, 103009. doi: 10.1016/j.agsy.2020.103009

Hartwig, N. L., and Ammon, H. U. (2002). Cover crops and living mulches. *Weed Sci.* 50, 688–699. doi: 10.1614/0043-1745(2002)050[0688:AIACCA]2.0.CO;2

Hassan, W., Saba, T., Jabbi, F., Wang, B., Cai, A., and Wu, J. (2022). Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: a review. *Int. Soil Water Conserv. Res.* 10, 530–545. doi: 10.1016/j.iswcr.2022.01.005

Hemathilake, D. M. K. S., and Gunathilake, D. M. C. C. (2022). "Agricultural productivity and food supply to meet increased demands," in *Future Foods* (Academic Press, Cambridge, MA), 539–553. doi: 10.1016/B978-0-323-91001-9.00016-5

Ivić, M., Grljušić, S., Plavšin, I., Dvojković, K., Lovrić, A., Rajković, B., et al. (2021). Variation for nitrogen use efficiency traits in wheat under contrasting nitrogen treatments in South-Eastern Europe. *Front. Plant Sci.* 12. doi: 10.3389/fpls.2021.682333

John, L. S., and Ogle, D. (2008). *Alsike Clover* (USDA). Available online at: http://www.peaceforageseed.ca/pdf/publications_pamphlets/alsike_clover_production_guide.pdf (Accessed March 30, 2025).

Khan, N., Ray, R. L., Sargani, G. R., Ihtisham, M., Khayyam, M., and Ismail, S. (2021). Current progress and future prospects of agriculture technology: gateway to sustainable agriculture. *Sustainability* 13, 4883. doi: 10.3390/su13094883

Khanal, N. (2022). Integration of perennial forage seed crops for cropping systems resiliency in the Peace River region of western Canada. *Can. J. Plant Sci.* 103, 1–12. doi: 10.1139/cjps-2022-0125

Khanal, N., Azooz, R., Rahman, N., Klein-Gebbinck, H., Otani, J. K., Yoder, C. L., et al. (2021). Value of integrating perennial forage seed crops in annual cropping sequences. *Agron. J.* 113, 4064–4084. doi: 10.1002/agj2.20781

Larsen, S. U., Manevski, K., Lærke, P. E., and Jørgensen, U. (2024). Biomass yield, crude protein yield and nitrogen use efficiency over nine years in annual and perennial cropping systems. *Eur. J. Agron.* 161, 127336. doi: 10.1016/j.eja.2024.127336

Lavkulich, L. M., and Arocena, J. M. (2011). Luvisolic soils of Canada: Genesis, distribution, and classification. *Can. J. Soil Sci.* 91, 781–806. doi: 10.4141/cjss2011-014

Liang, X. (2023). Research on the influence of the law of diminishing marginal returns in agriculture. *Adv. Econ. Manage. Polit. Sci.* 8, 262–267. doi: 10.54254/2754-1169/8/20230323

Liang, Z., Xu, Z., Cheng, J., Ma, B., Cong, W. F., Zhang, C., et al. (2023). Designing diversified crop rotations to advance sustainability: A method and an application. *Sustain. Prod. Consum.* 40, 532–544. doi: 10.1016/j.spc.2023.07.018

Liu, Z., Hao, Z., Sha, Y., Huang, Y., Guo, W., Ke, L., et al. (2022). High responsiveness of maize grain yield to nitrogen supply is explained by high ear growth rate and efficient ear nitrogen allocation. *Field Crops Res.* 286, 108610. doi: 10.1016/j.fcr.2022.108610

Liu, K., Johnson, E. N., Blackshaw, R. E., Hossain, Z., and Gan, Y. (2019). Improving the productivity and stability of oilseed cropping systems through crop diversification. *Field Crops Res.* 237, 65–73. doi: 10.1016/j.fcr.2019.03.020

Liu, C., Plaza-Bonilla, D., Coulter, J. A., Kutcher, H. R., Beckie, H. J., Wang, L., et al. (2022). Diversifying crop rotations enhances agroecosystem services and resilience. *Adv. Agron.* 173, 299–335. doi: 10.1016/bs.agron.2022.02.007

Makino, A. (2011). Photosynthesis, grain yield, and nitrogen utilization in rice and wheat. *Plant Physiol.* 155, 125–129. doi: 10.1104/pp.110.165076

Martens, J. T., Entz, M., and Wonneck, M. (2013). *Ecological farming systems on the Canadian prairies. A path to profitability, sustainability and resilience* (Winnipeg, MB: University of Manitoba).

Martens, J. R. T., Entz, M. H., and Wonneck, M. D. (2015). Redesigning Canadian prairie cropping systems for profitability, sustainability, and resilience. *Can. J. Plant Sci.* 95, 1049–1072. doi: 10.4141/cjps-2014-173

McKey, D. (1994). "Legumes and nitrogen: the evolutionary ecology of a nitrogen-demanding lifestyle," in *Advances in legume systematics. Part 5. The Nitrogen Factor.* Eds. J. I. Sprent and D. McKey (Royal Botanic Gardens, Kew), 211–228.

Means, M., Crews, T., and Souza, L. (2022). Annual and perennial crop composition impacts on soil carbon and nitrogen dynamics at two different depths. *Renew. Agric. Food Syst.* 37, 437–444. doi: 10.1017/S1742170522000084

Menegat, S., Ledo, A., and Tirado, R. (2022). Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. *Sci. Rep.* 12, 1–13. doi: 10.1038/s41598-022-18773-w

Mihrete, T. B., and Mihretu, F. B. (2025). Crop diversification for ensuring sustainable agriculture, risk management and food security. *Glob. Chall.* 9, 2400267. doi: 10.1002/gch2.202400267

Mortensen, D. A., and Smith, R. G. (2020). Confronting barriers to cropping system diversification. *Front. Sustain. Food Syst.* 4. doi: 10.3389/fsufs.2020.564197

Mosier, S., Córdova, S. C., and Robertson, G. P. (2021). Restoring soil fertility on degraded lands to meet food, fuel, and climate security needs via perennialization. *Front. Sustain. Food Sys.* 5. doi: 10.3389/fsufs.2021.706142

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature* 490, 254–257. doi: 10.1038/nature11420

Nelson, D. W., and Sommers, L. E. (1982). "Total carbon, organic carbon, and organic matter," in *Methods of soil analysis: Part 2 chemical and microbiological properties*. Ed. A. L. Page (American Society of Agronomy, Madison, WI), 539–579. doi: 10.2134/agronmonogr9.2.2ed.c29

Nilsson, P., Bommarco, R., Hansson, H., Kuns, B., and Schaak, H. (2022). Farm performance and input self-sufficiency increases with functional crop diversity on Swedish farms. *Ecol. Econ.* 198, 107465. doi: 10.1016/j.ecolecon.2022.107465

Ojija, F. (2024). Perennial grasses: natural allies for soil health and biodiversity, climate change mitigation, and invasive plant management. *Grass Res.* 4, 1. doi: 10.48130/grares-0024-0019

Omara, P., Aula, L., Oyebiyi, F., and Raun, W. R. (2019). World cereal nitrogen use efficiency trends: review and current knowledge. *Agrosyst. Geosci. Environ.* 2, 1–8. doi: 10.2134/age2018.10.0045

Pandey, B. (2023). Effects of plant growth regulators on plant phenotypes and yield components of grass seed crops. University of Alberta, Edmonton, AB.

Picasso, V. D., Berti, M., Cassida, K., Collier, S., Fang, D., Finan, A., et al. (2022). Diverse perennial circular forage systems are needed to foster resilience, ecosystem services, and socioeconomic benefits in agricultural landscapes. *Grassl. Res.* 1, 123–130. doi: 10.1002/glr2.12020

Pittman, T. (2020). Too much fertilizer? An observational association between inputs at planting and crop yield on a Saskatchewan farming operation. *Can. J. Plant Sci.* 100, 435–444. doi: 10.1139/cjps-2019-0223

Pouliot, S. (2019). *How productivity gains affect farm income – part 1* (Farm Credit Canada, Regina, SK, Canada). Available online at: https://www.fcc-fac.ca/en/knowledge/economics/how-productivity-gains-affect-farm-income-part-one.

Qaim, M. (2020). Role of new plant breeding technologies for food security and sustainable agricultural development. *Appl. Econ. Perspect. Policy* 42, 129–150. doi: 10.1002/aepp.13044

Rajput, N. A., Atiq, M., Baig, M., Jamal, N., Wahab, M., and Ali, F. (2024). "Analyzing pest risk in the context of climate change," in *Plant Quarantine Challenges under Climate Change Anxiety* (Springer Nature Switzerland, Cham), 359–405. doi: 10.1007/978-3-031-56011-8_12

Reader, M. A., Revoredo-Giha, C., Lawrence, R. J., Hodge, I. D., and Galang, B. (2018). Farmers' spending on variable inputs tends to maximise crop yields, not profit. *Int. J. Agric. Manage.* 7, 30–40. doi: 10.5836/ijam/2018-07-30

Roesch-McNally, G. E., Arbuckle, J. G., and Tyndall, J. C. (2018). Barriers to implementing climate resilient agricultural strategies: the case of crop diversification in the US Corn Belt. *Glob. Environ. Change* 48, 206–215. doi: 10.1016/j.gloenvcha.2017.12.002

Sánchez, A. C., Kamau, H. N., Grazioli, F., and Jones, S. K. (2022). Financial profitability of diversified farming systems: a global meta-analysis. *Ecol. Econ.* 201, 107595. doi: 10.1016/j.ecolecon.2022.107595

Schenk, U., Manderscheid, R., Hugen, J., and Weigel, H. J. (1995). Effects of CO2 enrichment and intraspecific competition on biomass partitioning, nitrogen content and microbial biomass carbon in soil of perennial ryegrass and white clover. *J. Exp. Bot.* 46, 987–993. doi: 10.1093/jxb/46.8.987

Schlautman, B., Bartel, C., Diaz-Garcia, L., Fei, S., Flynn, S., Haramoto, E., et al. (2021). Perennial groundcovers: an emerging technology for soil conservation and the sustainable intensification of agriculture. *Emerg. Top. Life Sci.* 5, 337–347. doi: 10.1042/ETLS20200318

Sharma, L. K., and Bali, S. K. (2017). A review of methods to improve nitrogen use efficiency in agriculture. *Sustainability* 10, 51. doi: 10.3390/su10010051

Šidlauskaitė, G., and Kadžiulienė, Ž. (2023). The effect of inorganic nitrogen fertilizers on the quality of forage composed of various species of legumes in the Northern part of a Temperate Climate Zone. *Plants* 12, 3676. doi: 10.3390/plants12213676

Skersiene, A., Slepetiene, A., Stukonis, V., and Norkeviciene, E. (2023). Accumulation of SOC and carbon fractions in different age red fescue permanent swards. *Land* 12, 1025. doi: 10.3390/land12051025

Skersiene, A., Slepetiene, A., Stukonis, V., and Norkeviciene, E. (2024). Contributions of different perennial grass species and their roots' characteristics to soil organic carbon accumulation. *Sustainability* 16, 6037. doi: 10.3390/su16146037

Tang, J., Li, W., Wei, T., Huang, R., and Zeng, Z. (2024). Patterns and mechanisms of legume responses to nitrogen enrichment: a global meta-analysis. *Plants* 13, 3244. doi: 10.3390/plants13223244

Thiagarajan, A., Fan, J., McConkey, B. G., Janzen, H. H., and Campbell, C. A. (2018). Dry matter partitioning and residue N content for 11 major field crops in Canada adjusted for rooting depth and yield. *Can. J. Soil Sci.* 98, 574–579. doi: 10.1139/cjss-2017-0144

Tilman, D., Reich, P. B., and Knops, J. M. (2006). Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature* 441, 629–632. doi: 10.1038/nature04742

Timlick, J. (2023). *A new approach provides evidence to support the benefits of diversified rotations* (Grainews Glacier FarmMedia, Winnipeg, MB, Canada. Available online at: https://www.grainews.ca/features/a-new-approach-provides-evidence-to-support-the-benefits-of-diversified-rotations/.

Vico, G., and Brunsell, N. A. (2018). Tradeoffs between water requirements and yield stability in annual vs. perennial crops. *Adv. Water Resour.* 112, 189–202. doi: 10.1016/j.advwatres.2017.12.014

Weih, M., Asplund, L., and Bergkvist, G. (2011). Assessment of nutrient use in annual and perennial crops: a functional concept for analyzing nitrogen use efficiency. *Plant Soil* 339, 513–520. doi: 10.1007/s11104-010-0599-4

Weih, M., Hamnér, K., and Pourazari, F. (2018). Analyzing plant nutrient uptake and utilization efficiencies: comparison between crops and approaches. *Plant Soil* 430, 7–21. doi: 10.1007/s11104-018-3738-y

Wen, G., Ma, B. L., Luce, M. S., Liu, K., Mooleki, P. S., Crittenden, S., et al. (2023). Optimizing nitrogen fertilization for hybrid canola (*Brassica napus* L.) production across Canada. *Field Crops Res.* 302, 109048. doi: 10.1016/j.fcr.2023.109048

Yang, Y., Gan, T. Y., and Tan, X. (2019). Spatiotemporal changes in precipitation extremes over Canada and their teleconnections to large-scale climate patterns. *J. Hydrometeorol.* 20, 275–296. doi: 10.1175/JHM-D-18-0004.1

Yang, T., Siddique, K. H., and Liu, K. (2020). Cropping systems in agriculture and their impact on soil health-a review. *Glob. Ecol. Conserv.* 23, e01118. doi: 10.1016/j.gecco.2020.e01118

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., et al. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. *Nat. Commun.* 15, 198. doi: 10.1038/s41467-023-44464-9

Yoder, C. (2004). *Timothy seed production in western Canada.* Available online at: http://www.peaceforageseed.ca/pdf/publications_pamphlets/Timothy_seed_production_guide.pdf (Accessed March 7, 2025).

Zahran, H. H. (1999). Rhizobium-legume symbiosis and nitrogen fixation under severe conditions and in an arid climate. *Microbiol. Mol. Biol. Rev.* 63, 968–989. doi: 10.1128/MMBR.63.4.968-989.1999

Zentner, R. P., Wall, D. D., Nagy, C. N., Smith, E. G., Young, D. L., Miller, P. R., et al. (2002). Economics of crop diversification and soil tillage opportunities in the Canadian prairies. *Agron. J.* 94, 216–230. doi: 10.2134/agronj2002.2160