Received: 19 November 2024 | Accepted: 1 March 2025

DOI: 10.1002/csc2.70047

Crop Science

ORIGINAL ARTICLE

Crop Ecology, Management & Quality

Immediate and second-year effects of preceding crops on wheat production in the Northern Great Plains

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Assigned to Associate Editor Curtis Adams.

Funding information
Western Grains Research Foundation; Alberta Grains; Agriculture and Agri-Food Canada; Saskatchewan Wheat Development Commission; Canadian Wheat Research Coalition; Saskatchewan Winter Cereals Development Commission

Abstract

Growers in the Northern Great Plains (NGP) are increasingly adopting winter wheat (WW; *Triticum aestivum* L.) into their crop rotations in years of ideal fall planting conditions due to its high yield potential. Our study evaluated WW responses to rotational crops, soybean (*Glycine max* L.) and lentil (*Lens culinaris* L.), field peas (*Pisum sativum* L.), faba bean (*Vicia faba* L.), canola (*Brassica napus* L.), flax (*Linum usitatissimum* L.), and oats (*Avena sativa* L.), and to different wheat rotational schemes following the rotational crop: WW-WW, hard red spring wheat (HRSW)-WW, and WW-HRSW. Although canola is traditionally favored for its snow-trapping benefits, soybean and lentil can achieve similar or superior results, enhancing both WW grain yields and protein concentrations when grown immediately after these two rotational crops. These benefits persisted in the second wheat phase in the WW–WW and HRSW–WW systems, albeit with increased variability. Canola stubble, while not offering immediate advantages for WW, contributed to high and stable yields in WW and HRSW when planted in the second year. However, a wheat yield drag was noted in the second year, especially affecting HRSW, indicating that monoculture cereal rotations are more detrimental to HRSW than to WW. In-crop growth patterns aligned with yield responses, with leguminous stubbles, especially lentil, promoting superior in-season growth compared to canola, flax, and oats. This study underscores WW as a viable option for cereal phases in the NGP cropping systems, contributing to enhanced ecological benefits in the local environment. By adopting WW in their cropping systems, growers can accrue synergistic benefits with multiple rotational crops.

Plain Language Summary

This study examined the effects of seven rotational crops (soybean, lentil, field peas, faba bean, canola, flax, and oats) on subsequent wheat grown in three

Abbreviations: AMMI, Additive Main effects and Multiplicative Interaction; CV, coefficient of variation; HRSW, hard red spring wheat; LAI, Leaf Area Index; NDVI, Normalized Difference Vegetation Index; PLS, Partial Least Squares; WW, winter wheat.

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rotational schemes (WW-WW, hard red spring wheat [HRSW]-WW, and WW-HRSW) in the Northern Great Plains (NGP). We observed that soybeans and lentils not only enhanced WW grain yields and protein concentration in the first wheat phase but also improved the second wheat phase, despite increased variability. WW generally outperformed HRSW in monoculture cereal systems, particularly in the second year after rotational crops, although both wheat types experienced yield reductions in the second wheat phase. The study highlights the benefits of diverse crop rotations and confirms that WW is a viable option for cereal phases in Canadian cropping systems.

1 | INTRODUCTION

Crop rotational diversity can lead to increased and stabilized yield, enhanced nitrogen availability, reduced incidence of diseases and weeds, decreased reliance on synthetic chemical inputs, and improved resilience to multiple environmental stresses compared to monoculture (Gaudin et al., 2015; Krupinsky et al., 2006; San Martín et al., 2019; Soon & Arshad, 2004). Proper sequencing of crops is crucial for successful dynamic cropping systems, influencing both yield improvement and disease management. Conversely, improper choice of rotational crops can reduce both yield and economic stability of the system as a consequence of elevated pest threats such as weed and disease infestations.

Wheat (*Triticum aestivum* L.) is often grown in Canada as the dominant cereal phase in rotation with other commodities including legumes and oilseeds (Beres et al., 2020). Studies conducted in the Northern Great Plains (NGP) observed that winter wheat (WW) outyielded spring wheat (SW) by an average of 36% (Entz & Fowler, 1991). Similarly, research in Europe reported that WW produced 42% higher grain yields compared to SW (Thorup-Kristensen et al., 2009). Additionally, Lollato and Edwards (2015) estimated that under non-limiting conditions in the Southern Great Plains, the maximum attainable WW grain yield could reach 7.68 Mg ha^{-1}. As such, growers in the NGP are interested in incorporating WW into their crop rotations to boost crop yield and improve crop competitiveness with weed, disease, and insect pests. Wang et al. (2024) noted that including WW also facilitates better workload management during seeding and harvest. However, drought stress in early spring, a significant challenge under current climatic conditions, adversely affects wheat productivity (Rashid et al., 2022) and is expected to occur more frequently with climate change (Jacques et al., 2021). Diversifying rotations and reducing tillage can improve yields even in challenging conditions. For instance, during hot and dry years in Eastern Canada, diversifying corn (*Zea mays* L.)–soybean (*Glycine max* L.) and reducing tillage increased corn and soybean yields by 7% and 22%, respectively (Gaudin et al., 2015). Although the benefits of rotation vary with crops, weather patterns, and tillage practices (Gaudin et al., 2015), integrating wheat into more diverse rotations is expected to enhance yield stability.

Rotational crops can have varying effects on the subsequent crops. According to a review paper by Angus et al. (2015), wheat responds most positively when preceded by oats (*Avena sativa* L.), canola (*Brassica napus* L.), mustard (*Brassica juncea* L.), flax (*Linum usitatissimum* L.), field peas (*Pisum sativum* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* L.), or lupins (*Lupinus* sp. L.), in ascending order of favorable impact. Similarly, Groeneveld et al. (2024) observed that sugar beet (*Beta vulgaris* L.) and winter oilseed rape (*Brassica napus* L.) rotational crops provided superior benefits to a succeeding WW phase in Germany. Kirkegaard et al. (2004) also reported that *Brassica* oilseeds were an effective rotational crop to control crown rot in bread wheat in Australia.

Leguminous rotational crops, such as field peas, provide benefits not only to the first subsequent crop but also to the second one. Kumar and Goh (2002) observed that residues from white clover (*Trifolium repens* L.) and field peas continued to provide benefits for two and one subsequent wheat crops, respectively, in New Zealand. Arshad et al. (1998) reported significantly higher grain yield and above-ground dry matter in the first wheat crop compared to the second in systems involving field peas-wheat-wheat, canola-wheat-wheat, and fallow-wheat-wheat in the NGP. In the same region, Soon and Arshad (2004) observed similar positive wheat responses to rotational crops, attributing the superior yield of the second wheat phase following field peas to greater nitrogen availability, particularly below 25-cm soil depth. Conversely, Angus et al. (2015) noted diminishing effects of rotational crops on the second and third wheat phases compared to the first in Australia.

Despite the well-established benefits of rotational diversity, the immediate impacts of preceding crops on the performance of subsequent wheat phases in the NGP are not fully documented. Moreover, the range of crop options for

diversification continues to expand on account of emerging markets and a changing climate. One example is the westward expansion of soybean in Canada. This study aims to quantify the effects of diverse rotational crops on both the immediate (first) and second wheat phases, with a particular focus on WW and hard red spring wheat (HRSW) systems. The objectives of this study were to (1) evaluate the environmental and economic benefits of WW compared to HRSW and (2) assess both WW and HRSW responses to leguminous, oilseed, and cereal rotational crops. By evaluating the influence of these rotational crops, the research will provide a comprehensive understanding of how rotational diversity impacts wheat yield stability. This study will also provide growers with valuable insights to optimize rotational schemes for improved wheat productivity and sustainability.

Core Ideas

- Wheat responses to rotational crops in the Northern Great Plains often rely on information generated from other production regions.
- In years of optimal fall planting conditions, growers may consider winter wheat but uncertainty of preceding crop stubble compatibility aside from canola is an obstacle to adoption.
- Soybean and lentil rotational crops were superior in terms of enhanced winter wheat (WW) grain yields and protein concentration.
- The benefits of soybean and lentil persisted in a subsequent second wheat phase in the WW–WW and hard red spring wheat (HRSW)–WW systems.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

Field experiments were conducted at four locations across western Canada—Lethbridge (Alberta), Saskatoon, Indian Head (Saskatchewan), and Brandon (Manitoba)—over the period from 2018 to 2022. A comprehensive set of soil, agronomic, and environmental data for each site-year is summarized in Table 1. The study involved two main sets of treatments: (i) seven rotational crops (soybean, lentil, field peas, faba bean, canola, flax, and oats) and (ii) three 2-year wheat rotation systems as the succeeding wheat phases (WW-WW, HRSW-WW, and WW-HRSW). The rotational crops were planted in 2018, 2019, and 2020 to establish stubbles for the two wheat phases, which were subsequently planted in 2019, 2020, 2021, and 2022. The WW and HRSW cultivars used in this study were a Canada Western Red Winter, AAC Wildfire (Graf et al., 2016), and a Canada Western Red Spring, AAC Viewfield (Cuthbert et al., 2018), respectively. The treatments of this study were arranged in a factorial randomized complete block design with four replicates, resulting in a total of 84 plots (21 treatments × 4 replicates) at each location. The plot dimensions varied by location, ranging from 3.4 to 3.7 m in width and 10 to 15 m in length.

2.2 | Seeding operations and experimental procedures

Each plot was treated with glyphosate (RoundUp, Bayer CropScience Canada) a few days before seeding, applied at a rate of 900 g a.i. ha^{-1} using a motorized sprayer calibrated to deliver a carrier volume of 45 L water ha^{-1} at 275 kPa pressure. The seeds of both WW and HRSW were treated with Raxil Pro (tebuconazole (3.0 g L^{-1}), prothioconazole (15.4 g L^{-1}), and metalaxyl (6.2 g L^{-1}) (Bayer CropScience Canada) plus Stress Shield (Imidacloprid (600 g L^{-1}) (Bayer CropScience Canada). Plots were direct-seeded at a rate of 450 seeds m^{-2} using a commercial zero tillage air drill (Model CP 129A, ConservaPak) equipped with an air delivery system (Valmar Airflo Inc.) and knife openers spaced 23 cm apart, or a comparably configured plot seeder. All WW and HRSW plots received phosphorus ($NH_4H_2PO_4$; 11-52-0) and potassium (KCl; 0-0-60) fertilizers in the fall before planting, based on soil test results (Western Ag Labs PRS soil test system). Nitrogen fertilizer (1:1 blend of urea and environmentally smart N; H_2NCONH_2; 45-0-0) was banded at the time of planting according to soil test recommendations. Fungicides were applied near the wheat heading based on site conditions and disease presence.

2.3 | Data collection

For the two wheat phases, we collected post-emergent plant counts for both WW and HRSW, spring plant counts for WW, early- and late-season vigor, head density, as well as key agronomic indicators such as Normalized Difference Vegetation Index (NDVI), leaf area index (LAI) and chlorophyll index (Chl), grain yield (Mg ha^{-1}; at 13.5% moisture basis), 1000-kernel weight (g) test weight (kg hL^{-1}), and whole grain protein concentration (g kg^{-1}).

Post-emergent plant counts were conducted at the two to three leaf stages to determine the number of viable plants. This involved staking and counting 1-m segments within the plot, specifically from the second, third, second-to-last, and third-to-last rows. Plant density (plants m^{-2}) was calculated by dividing the total count of viable plants by the

TABLE 1 Soil, agronomic, and environment data for experimental site-years (2019–2022) in Alberta, Saskatchewan and Manitoba.

Location, year and wheat phase	Latitude, longitude	Crop	SOM	Soil pH	Soil N (lb/ac)	Seeding date	Harvest date	GDD (°C)	Mean temperature (°C)	Precipitation (mm)	Statistical power		
											RC	CR	RC × CR
Lethbridge, AB													
2019, first wheat	49.704163°, −112.691145°	WW	NA	8.2	220.3	9/17/2018	8/21/2019	1433.2	4.8	205.5	0.013	0.007	2.10E-05
	49.704163°, −112.691145°	HRSW	NA	8.2	220.3	4/24/2019	8/31/2019	1303.8	15.3	124.5			
2020, second wheat	49.704163°, −112.691145°	WW	NA	8.2	65	9/27/2019	8/12/2020	1293.4	4.7	263.4	0.011	0.390	1.42E-05
	49.704163°, −112.691145°	HRSW	NA	8.2	65	5/28/2020	9/12/2020	1317.6	18	159.7			
2020, first wheat	49.702945°, −112.691152°	WW	NA	8.2	73.9	9/27/2019	8/13/2020	1306.3	4.7	263.4	0.021	0.282	1.58E-06
	49.702945°, −112.691152°	HRSW	NA	8.2	73.9	5/25/2020	9/12/2020	1345.7	17	164.1			
2021, second wheat	49.702945°, −112.691152°	WW	NA	8.3	41.1	9/22/2020	8/5/2021	1506.9	6.1	150	0.000	0.088	0.000
	49.702945°, −112.691152°	HRSW	NA	8.3	41.1	4/21/2021	8/11/2021	1293.6	16.5	76			
2021, first wheat	49.704195°, −112.692781°	WW	NA	8.2	26.1	9/22/2020	8/4/2021	1490.4	6.0	150	2.55E-06	0.354	0.008
	49.704195°, −112.692781°	HRSW	NA	8.2	26.1	4/21/2021	8/12/2021	1309.3	16.5	76			
2022, second wheat	49.704195°, −112.692781°	WW	NA	8.1	81	9/15/2021	8/16/2022	1606.9	6.0	279	0.007	0.016	0.000
	49.704195°, −112.692781°	HRSW	NA	8.1	81	4/26/2022	8/30/2022	1429.4	16.6	231			
Brandon, MB													
2019, first wheat	50.032417°, −99.887417°	WW	NA	8.1	36.8	9/6/2018	8/19/2019	1327.7	0.3	324.4	0.000	0.003	1.51E-06
	50.032417°, −99.887417°	HRSW	NA	8.1	36.8	5/13/2019	9/4/2019	1310.0	16.5	230.5			
2020, second wheat	50.032417°, −99.887417°	WW	NA	8.2	6.3	9/17/2019	8/11/2020	1310.4	1.2	485.1	4.98E-05	0.003	3.35E-09
	50.032417°, −99.887417°	HRSW	NA	8.3	1.3	5/21/2020	8/31/2020	1348.2	13.1	318.5			

(Continues)

TABLE 1 (Continued)

Location, year and wheat phase	Latitude, longitude	Crop	SOM	Soil pH	Soil N (lb/ac)	Seeding date	Harvest date	GDD (°C)	Mean temperature (°C)	Precipitation (mm)	Statistical power		
											RC	CR	RC × CR
2020, first wheat	50.032417°, −99.887417°	WW	NA	8.3	7.6	9/27/2019	8/11/2020	1215.4	0.7	357.7	3.38E-05	0.488	0.003
	50.032417°, −99.887417°	HRSW	NA	8.3	9.3	5/21/2020	8/31/2020	1348.2	13.1	318.5			
2021, second wheat	50.032417°, −99.887417°	WW	NA	8.1	52.5	9/10/2020	8/16/2021	1516.6	2.4	260.4	0.000	0.027	0.004
	50.032417°, −99.887417°	HRSW	NA	8.2	45	5/5/2021	8/30/2021	1418.7	16.8	308.0			
2021, first wheat	50.032194°, −99.885944°	WW	5	8.1	33.6	9/18/2020	8/16/2021	1476.0	2.2	259.0	2.01E-05	0.293	0.009
	50.032194°, −99.885944°	HRSW	5	8.1	23	5/6/2021	8/30/2021	1418.7	16.9	308.0			
2022, second wheat	50.032194°, −99.885944°	WW	NA	8	29.2	9/14/2021	8/25/2022	1593.2	1.4	425.7	0.000	0.019	0.008
	50.032194°, −99.885944°	HRSW	NA	8.3	25.9	5/26/2022	9/12/2022	1429.8	18.1	183.3			
Indian Head, SK													
2019, first wheat	NA	WW	NA	NA	NA	NA	9/7/2019	NA	NA	NA	1.16E-10	0.031	0.001
	NA	HRSW	NA	NA	NA	5/8/2019	9/7/2019	1213.7	15.1	225.8			
2020, second wheat	NA	WW	NA	NA	NA	9/25/2019	8/24/2020	1298.9	1.4	214.9	3.18E-06	0.003	1.72E-08
	NA	HRSW	NA	NA	NA	5/25/2020	9/1/2020	1172.5	17	89.4			
2020, first wheat	NA	WW	NA	NA	NA	9/25/2019	8/24/2020	1298.9	1.4	214.9	1.94E-10	0.050	8.60E-12
	NA	HRSW	NA	NA	NA	5/25/2020	9/2/2020	1177.7	16.9	97.3			
2021, second wheat	50.54°, −103.65°	WW	NA	NA	15.4	9/16/2020	9/2/2021	1583.6	2.9	378.6	1.79E-05	0.004	1.76E-05
	50.54°, −103.65°	HRSW	NA	NA	15.4	5/7/2021	9/2/2021	1368.8	16.5	295.1			
2021, first wheat	50.54°, −103.65°	WW	NA	NA	15.4	9/15/2020	9/8/2021	1634.8	3.1	378.6	2.32E-11	0.013	4.00E-12
	50.54°, −103.65°	HRSW	NA	NA	15.4	5/7/2021	8/30/2021	1335.4	16.6	294.9			
2022, second wheat	50.54°, −103.65°	WW	NA	NA	15.4	9/20/2021	9/3/2022	1552.1	1.6	421.3	0.042	0.003	2.71E-05
	50.54°, −103.65°	HRSW	NA	NA	15.4	6/1/2022	9/12/2022	1290.7	17.4	187.9			

(Continues)

TABLE 1 (Continued)

Location, year and wheat phase	Latitude, longitude	Crop	SOM	Soil pH	Soil N (lb/ac)	Seeding date	Harvest date	GDD (˚C)	Mean temperature (˚C)	Precipitation (mm)	Statistical power		
											RC	CR	RC × CR
Saskatoon, SK													
2019, first wheat	52.150278˚, −106.544167˚	WW	4.5	7.5	18	NA	NA	NA	NA	NA	1.24E-08	0.921	7.61E-06
	52.150278˚, −106.544167˚	HRSW	4.5	7.5	18	NA	NA	NA	NA	NA			
2020, second wheat	52.150278˚, −106.544167˚	WW	4.5	7.2	NA	9/17/2019	8/24/2020	1410.4	1.2	287.5	2.09E-09	0.098	1.04E-06
	52.150278˚, −106.544167˚	HRSW	NA	NA	NA	5/11/2020	8/24/2020	1241.8	16.7	196.2			
2020, first wheat	NA	WW	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	NA	HRSW	NA	NA	NA	NA	NA	NA	NA	NA			
2021, second wheat	52.150278˚, −106.544167˚	WW	4.5	7.2	NA	9/4/2020	8/11/2021	1503.8	2.2	154.0	NA	NA	NA
	52.150278˚, −106.544167˚	HRSW	4.5	7.2	NA	5/11/2021	8/11/2021	1209.8	17.9	101.6			
2021, first wheat	NA	WW	NA	NA	NA	NA	NA	NA	NA	NA	4.32E-05	0.396	0.000
	NA	HRSW	NA	NA	NA	NA	NA	NA	NA	NA			
2022, second wheat	52.150278˚, −106.544167˚	WW	5	7.2	50	9/9/2021	8/22/2022	1533.2	1.6	198.0	1.48E-05	0.005	3.63E-06
	52.150278˚, −106.544167˚	HRSW	5	7.2	50	5/2/2022	8/22/2022	1273.1	16.3	130.6			

Abbreviations: CR, crop rotation; GDD, growing degree days (base temperature is 5˚C for GDD calculation); HRSW, hard red spring wheat; NA, not available; RC, rotational crop; SOM, soil organic matter; WW, winter wheat.

product of row spacing and the number of rows counted. In the spring, the WW plants in the second and the second-to-last two rows were destructively sampled and counted. Head density (heads m^{-2}) was assessed by evaluating heads from the staked third and third-to-last rows at physiological maturity. The number of heads per plant was determined by dividing the total head count by the number of plants in each designated area. Early-season vigor was evaluated at the Feekes (Large, 1954) 6 growth stage, while late-season vigor was assessed at Feekes 8. Vigor was rated on a scale of "1"–"5" with "1" representing poor vigor with light color and "5" representing vigorous growth with bright green color. The parameters NDVI, LAI, and Chl index were determined from the Feekes 4 to Feekes 11 growth stages using a LP-80 AccuPAR LAI Ceptometer (METER Group, Inc.), GreenSeeker optical sensor (NTech Industries Incorporation), and a FieldScout CM1000 chlorophyll meter (Spectrum Technologies, Inc.), respectively, following the procedures described in Beres et al. (2018a).

Wheat plots were harvested with a plot combine equipped with a straight-cut header, pickup reel, and crop lifters. Grain yield was calculated and corrected to 13.5% moisture. A 2 kg subsample was retained to measure 1000-kernel weight and test weight. Whole grain protein concentration was determined from the same subsample using near-infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc.). Drought stress (drought monitor: Dm) data were derived from https://open.canada.ca/data/en/dataset/292646cd-619f-4200-afb1-8b2c52f984a2.

The drought stress data are produced monthly by the Canadian Drought Monitor. It is developed from NDVI, streamflow values, Palmer Drought Index, and other drought indicators. Data are classified as no drought (0), abnormally dry (1), moderate drought (2), severe drought (3), extreme drought (4), and exceptional drought (5).

2.4 | Statistical analyses

A Univariate mixed model analysis was performed for all yield and quality variables using the MIXED and GLIMMIX procedures of SAS 15.3 (Littell et al., 2006; SAS Institute, 2023). A preliminary analysis with PROC MIXED was conducted with heterogeneous residual variances modeled to estimate starting covariance parameter values. These covariance estimates were then passed on to a subsequent PROC GLIMMIX analysis using the PARMS statement (SAS Institute, 2023). Residual heterogeneity was addressed using the REPEATED statement in PROC MIXED and the RANDOM statement in PROC GLIMMIX. A Gaussian error distribution was specified for the PROC GLIMMIX analyses.

Early- and late-season vigor was treated as a multinomial ordinal variable with ratings ranging from 2 to 5 and was analyzed using PROC GLIMMIX of SAS 15.3 (Anonymous, 2019; SAS Institute, 2023). Default estimation methods were used with a multinomial error distribution and a cumulative logit link function. PROC GLIMMIX output was passed on to PROC PLM (SAS Institute, 2023) to calculate cumulative probabilities for each level of crop rotation and rotational crop. These cumulative probabilities were used to estimate the probability of each vigor level (2, 3, 4, and 5) occurring for different crop rotation and rotational crop levels. The number of observations for each vigor level, phase, crop rotation, and rotational crop combination was summarized, along with the associated probabilities, to aid in interpreting the results.

The in-season growth responses, NDVI, LAI, and Chl index, were collected on different dates during the growing season due to uneven data collection across dates and variability in growth stages among sites. Therefore, data were averaged for each site, phase, crop rotation, rotational crop, and replicate combination to facilitate data analysis. In-season growth responses were analyzed with PROC GLIMMIX of SAS 15.3 (SAS Institute, 2023) using a Gaussian error distribution. This analysis did not incorporate heterogeneous residual variances because it yielded unstable results.

All analyses were conducted separately for each wheat phase. For yield, quality, and vigor data, replicate and site effects (combinations of location and year) were treated as random, while rotational crop, crop rotation effects, and their interactions were considered fixed. For in-season growth data, replicate was treated as a random effect, and site, crop rotation, and rotational crop were fixed effects. Effects were considered significant if the associated p-value was ≤ 0.05. Least significant difference ($LSD_{0.05}$) values were reported with least-squares means to indicate the precision of mean differences for analyses using Gaussian error distribution.

A mean-coefficient of variation (CV) biplot methodology, originally developed by Francis and Kannenberg (1978), was used to explore treatment responses and variability for yield and protein concentration. Seed yield and protein concentration were analyzed separately for each wheat phase using an environmental variance mixed model as described by Piepho (1999). This analysis was conducted using the MIXED and GLIMMIX procedures in SAS 15.3 (SAS Institute, 2023), with model specifications similar to those for analyses of most variables (first paragraph in the Statistical Methods section) with exceptions. The random statements for PROC MIXED and GLIMMIX were replaced with the following statements for the environmental variance model:

```
RANDOM intercept/subject = replicate(site);
RANDOM crop rotation × rotational crop/subject
= site type = fa(1);
```

The least-squares means were calculated for combinations of rotational crop and crop rotation. A CV for each treatment combination was derived from covariance estimates generated from the second random statement. The means were plotted against CV to generate the biplot. The biplot data were subsequently categorized into four groups. Group I comprised treatments with high mean grain yield and high stability, Group II included treatments with high mean grain yield and low stability, Group III consisted of treatments with low mean grain yield and low stability, and Group IV encompassed treatments with low mean grain yield and high stability.

Additionally, an analysis of variance was performed by site and replicate as a random effect and crop rotation and rotational crop as fixed effects. Statistical power was calculated for the main effects and interaction effect according to methods described by Stroup (2012). The results from this analysis were used to investigate sources of site-by-treatment variability (Table 1).

Multivariate partial least squares (PLS) regression combined with additive main effects and multiplicative interaction (AMMI) methods was employed to analyze treatment-by-environment interactions for crop yield in relation to weather-related variables (Crossa et al., 2015). The results of this analysis were summarized in a biplot. The factorial combinations of rotational crop and crop rotation effects were consolidated into a single treatment. Treatment least-squares means were estimated separately for each environment (location × year) and saved for further analysis using PROC MIXED of SAS 15.3 (SAS Institute, 2023), with replicates as a random effect and treatments as a fixed effect. The least-squares means were then analyzed with a PROC GLM (SAS Institute, 2023) model including environment and treatment main effects to estimate a matrix of residuals for each environment by treatment combination.

Environmental data were compiled from precipitation (including irrigation) and growing degree days (GDD; calculated with a base temperature of 0°C) from May 1 to September 30, along with mean temperature and Dm data provided in Table 1. The residual matrix from PROC GLM and the environmental dataset were standardized to a mean of 0 and a standard deviation of 1 using PROC STANDARD (SAS Institute, 2023). The two standardized datasets were then merged and analyzed using PROC PLS (SAS Institute, 2023). For this analysis, the residual matrix data served as responses, and environmental data were treated as explanatory variables. Scores, x-loading, and y-loading estimates for the first two latent variables (dimensions) were extracted and formatted for plotting. PROC IML (SAS Institute, 2023) was used to prepare and format PLS scores. Scores for each environment (location × year) and treatment y-loading values were plotted as points, while weather variable x-loading estimates were represented as vectors emanating from the origin.

3 | RESULTS AND DISCUSSION

3.1 | Wheat grain yield response to rotational crop and crop rotation

The statistical power analysis revealed a high probability of detecting significant yield responses at the 5% level for rotational crops in several cases: at Lethbridge 2019 for the first wheat phase, at Lethbridge 2020 for both first and second wheat phases, and at Indian Head 2020 for the second wheat phase (Table 1). Additionally, there was a greater likelihood of detecting significant crop rotation effects at Lethbridge 2020 for both the first and second wheat phases, at Brandon 2020 for the first wheat phase, and at Brandon 2021 for the first wheat phase. However, the analysis indicated a low probability of detecting significant rotational crop by crop rotation effects across all site-years.

Differences among rotational crops were observed in grain yield and 1000-kernel weight, but not in plant density, head density, or heads per plant in the first wheat phase (Table 2). However, plant density was influenced by crop rotation. In the second wheat phase, rotational crops did not affect any yield variables (Table 3), though crop rotation did impact grain yield and 1000-kernel weight. In research conducted in the Canadian Prairies, Mooleki et al. (1998) noted that when nitrogen availability has minimal impact on grain yield in a rotation system, water redistribution becomes a more dominant factor, and WW relies on early spring moisture in dry climates. According to Domitruk et al. (2000), the rapid growth of WW under cool temperatures in April and early May depleted much of the available water in the top 50 cm of the soil profile in the Canadian Prairies. The lack of grain yield response to crop rotation in the first wheat phase indicates that WW yielded similarly to HRSW (Table 2; $p = 0.214$). This result suggests that early-season soil moisture, vital for WW yield potential, was likely limited or absent in many environments during the experimental period.

Research conducted in the Canadian Prairies revealed that diverse crop rotations can improve soil health by enhancing soil microbial communities and carbon concentration, which are linked to better soil fertility (Beres et al., 2018a; Lupwayi et al., 1998). The improved soil organic carbon and nitrogen contents, in turn, resulted in more plant-available mineral nitrogen and consequently more vigorous crop growth for wheat (Agenbag, 2012). Effects of rotational crops on yields of the subsequent wheat phases vary in this study. In the first wheat phase, leguminous crop stubbles significantly boosted grain yields for both WW and HRSW, with soybean and lentil stubbles producing higher yields compared to other rotational crops.

Previous research has noted that incorporating leguminous crops into rotation systems enhances agricultural sustainability in semiarid NGP regions by increasing soil nitrogen levels

TABLE 2 Analysis of variance for the first wheat phase collected at environments across the Canadian Prairies from 2019 to 2022.

	Yield	1000-kernel weight	Plant density	Head density	Head per plant	Protein concentration	Test weight
	p-values						
RC	<0.001***	0.002**	0.244	0.387	0.231	0.814	0.13
CR	0.214	0.075	0.011**	0.881	0.861	0.000***	0.091
RC × CR	0.413	0.336	0.167	0.748	0.416	0.167	0.567
	Covariance						
Site	93.30%	88.90%	89.30%	80.50%	56.90%	62.90%	91.80%
Site × RC	1.30%	1.10%	9.00%	5.00%	12.70%	8.10%	1.90%
Site × CR	5.00%	9.00%	0.00%	10.20%	25.90%	24.30%	5.70%
Site × RC × CR	0.30%	1.10%	1.70%	4.30%	4.50%	4.80%	0.50%
	p-values						
Site	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Site × RC	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Site × CR	<0.001***	<0.001***	1	<0.001***	<0.001***	<0.001***	<0.001***
Site × RC × CR	<0.001***	<0.001***	0.009**	<0.001***	<0.001***	<0.001***	<0.001***

Abbreviations: CR, crop rotation; RC, rotational crop.
** and *** denote significant effects at $p \leq 0.01$ and $p \leq 0.001$, respectively.

TABLE 3 Analysis of variance for the second wheat phase collected at environments across the Canadian Prairies from 2019 to 2022.

	Yield	1000-kernel weight	Plant density	Head density	Head per plant	Protein concentration	Test weight
	p-values						
RC	0.583	0.123	0.313	0.374	0.129	0.239	0.808
CR	0.002**	0.006**	0.067	0.537	0.178	<0.001***	0.553
RC × CR	0.47	0.904	0.091	0.517	0.107	0.928	0.323
	Covariance						
Site	95.40%	84.10%	98.00%	68.80%	70.20%	68.80%	92.30%
Site × RC	1.50%	0.60%	0.10%	0.80%	0.70%	2.10%	0.70%
Site × CR	2.80%	14.70%	0.50%	27.10%	27.50%	22.00%	6.50%
Site × RC × CR	0.20%	0.70%	1.40%	3.20%	1.60%	7.20%	0.40%
	p-values						
Site	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
Site × RC	<0.0001***	<0.0001***	0.809	0.134	0.104	0.042*	<0.0001***
Site × CR	<0.0001***	<0.0001***	0.149	<0.0001***	<0.0001***	<0.0001***	<0.0001***
Site × RC × CR	<0.0001***	<0.0001***	0.001**	<0.0001***	0.005**	<0.0001***	<0.0001***

Abbreviations: CR, crop rotation; RC, rotational crop.
** and *** denote significant effects at $p \leq 0.01$ and 0.001, respectively.

(Entz et al., 2002; Lupwayi & Soon, 2016; Zentner et al., 2001) (Tables 2 and 4). Specifically, WW grown after oats and HRSW grown after flax had lower grain yields compared to those preceded by leguminous crops (Table 4). Notably, WW yields were particularly responsive when grown on soybean and lentil stubbles in the first wheat phase and on soybean, lentil, and field peas in the second wheat phase. Our results also suggest that soybean and lentil have potential in sequence with WW, and the positive response following field peas in the second wheat phase confirms our previous research that these stubbles provide a comparable alternative to canola without the risk of jeopardizing grain yields (Irvine et al., 2013). Utilizing alternative crop stubble types may address the challenge of timely planting of WW in late-maturing canola fields. The rate of N_2 fixation varies considerably, depending on the type of legume cultivar (Beck, 1992), soil temperature, and

TABLE 4 The influence of rotational crops on two successive wheat plantings across the Canadian Prairies from 2019 to 2022.

			Rotational crop							
		Crop rotation	Soybean	Lentil	Field peas	Faba bean	Canola	Flax	Oats	$LSD_{0.05}$
Yield (Mg ha^{-1})	First phase	HRSW-WW	3.94a	3.91ab	3.75abcd	3.81abc	3.64bcd	3.53d	3.60cd	0.28
		WW-HRSW	4.26a	4.27a	4.04ab	4.08ab	3.84bc	3.89bc	3.65c	0.28
		WW-WW	4.36a	4.26ab	4.07bcd	4.12sbc	3.88cd	4.04bcd	3.80d	0.28
	Second phase	HRSW-WW	3.29	3.37	3.38	3.30	3.33	3.20	3.17	ns
		WW-HRSW	2.80	2.96	2.88	2.85	2.92	2.81	2.76	ns
		WW-WW	3.41	3.44	3.31	3.38	3.41	3.39	3.20	ns
1000-kernel weight (g)	First phase	HRSW-WW	33.0ab	33.1a	32.9ab	32.7abc	32.1bc	32.1bc	32.0c	0.9
		WW-HRSW	35.0a	34.2abc	33.7bc	34.4ab	33.6bc	34.2abc	33.4c	0.9
		WW-WW	35.4a	34.5b	34.0b	34.3b	33.6b	34.1b	33.8b	0.9
	Second phase	HRSW-WW	30.9	31.2	31.2	31.0	31.4	31.5	31.1	ns
		WW-HRSW	26.9	27.6	27.7	27.3	28.2	27.5	27.2	ns
		WW-WW	30.2	30.6	30.7	30.0	30.8	30.7	30.4	ns
Plant density (plant m^{-2})	First phase	HRSW-WW	410	383	202	255	217	296	281	ns
		WW-HRSW	215	253	242	217	264	247	241	ns
		WW-WW	222	231	232	207	256	250	231	ns
	Second phase	HRSW-WW	269	257	281	279	266	269	252	ns
		WW-HRSW	251	319	NA	NA	NA	136	NA	ns
		WW-WW	288	290	285	272	284	276	287	ns
Head density (head m^{-2})	First phase	HRSW-WW	313	329	330	322	320	314	299	ns
		WW-HRSW	323	326	332	298	323	330	300	ns
		WW-WW	323	330	325	318	335	329	315	ns
	Second phase	HRSW-WW	384	360	385	371	370	368	358	ns
		WW-HRSW	338	354	347	330	353	356	335	ns
		WW-WW	360	361	386	375	375	363	358	ns
Head per plant	First phase	HRSW-WW	1.9	1.7	1.8	1.8	1.8	1.7	1.6	ns
		WW-HRSW	2.3a	1.8bcd	1.7cd	1.8bcd	1.9bc	2.2ab	1.5d	0.4
		WW-WW	2.2	1.8	1.6	1.9	1.9	1.9	1.6	ns
	Second phase	HRSW-WW	1.8	1.7	1.9	1.8	1.8	1.8	1.9	ns
		WW-HRSW	2.1bc	2.1bc	2.1bc	2.0c	2.1bc	2.2ab	2.3a	0.2
		WW-WW	1.8	1.7	1.9	1.8	1.8	1.8	1.8	ns
Protein (g kg^{-1})	First phase	HRSW-WW	148.4	146.9	146.4	146.9	141.8	145.5	144.7	ns
		WW-HRSW	126.5	128.5	129.8	128.5	128.7	126.7	128.2	ns
		WW-WW	127.1	129.5	129.8	128.9	127.5	128.5	128.3	ns
	Second phase	HRSW-WW	128.4	128.9	126.2	127.6	125.5	127.0	128.7	ns
		WW-HRSW	153.5	153.8	155.2	154.5	153.2	152.8	157.3	ns
		WW-WW	127.9	129.2	129.4	130.7	125.7	128.2	130.3	ns

(Continues)

TABLE 4 (Continued)

			Rotational crop							
		Crop rotation	Soybean	Lentil	Field peas	Faba bean	Canola	Flax	Oats	$LSD_{0.05}$
Test weight (kg hL^{-1})	First phase	HRSW-WW	78.9	78.6	78.6	78.7	78.4	78.4	77.9	ns
		WW-HRSW	77.8	77.5	77.4	77.5	77.1	77.7	77.0	ns
		WW-WW	78.0	77.7	77.5	77.6	77.3	77.9	77.2	ns
	Second phase	HRSW-WW	74.8	74.7	74.9	74.9	75.1	75.1	75.1	ns
		WW-HRSW	74.2	74.7	74.2	74.7	74.6	74.2	74.0	ns
		WW-WW	73.9	74.3	74.1	74.0	74.5	74.6	74.0	ns

Note: The crops in the first wheat phase are HRSW in the HRSW-WW, WW in the WW-HRSW and the first WW in the WW–WW systems, which are grown immediately after the preceding crops. The crops in the second wheat phase are WW in the HRSW-WW, HRSW in the WW-HRSW and the second WW in the WW-WW, which are grown in the second year after the rotational crops.

Abbreviations: HRSW, hard red spring wheat; ns, not significant; WW, winter wheat. Means followed by the same letter are not significantly different ($p < 0.05$).

moisture, as well as soil NO_3 level (Herridge et al., 1995). That is the reason why not all the leguminous crops displayed consistent influence on the subsequent wheat phases. In the second wheat phase, the average grain yield decreased by 18%, 17%, and 24% for WW in the HRSW–WW and WW–WW systems, and HRSW in the WW–HRSW system, respectively, compared to the first wheat phase (data not shown). Additionally, a significant yield drag was observed in HRSW compared to WW in the second wheat phase (Table 4), indicating that monoculture cereal rotations have a more detrimental effect on HRSW than on WW. In other words, WW can still achieve a decent grain yield in the second year following rotational crops. The highest persistence of yield benefits in the second wheat phase occurred after canola in the WW–WW system, with only a 12% reduction in yield.

Reductions with other rotational crops ranged from 13% to 29%. Similarly, the 1000-kernel weight notably decreased in the second wheat phase compared to the first wheat phase, particularly for HRSW, regardless of the rotational crops. In Eastern Europe, Seibutis and Deveikyte (2008) also observed the lowest 1000-kernel weight in the second-year wheat of a field peas-wheat-wheat system, consistent with our findings.

The biplot in Figure 1 illustrates that soybean and lentil stubbles consistently achieved superior and stable yields for WW in the first wheat phase, while oats stubble resulted in lower and more variable yields. Soybean and lentil, as well as faba bean stubbles, also benefited HRSW, providing high and consistent yields. In contrast, oats and flax stubbles produced below-average and more variable yields for HRSW in the HRSW–WW system. In the second wheat phase, the benefits of soybean stubble persisted in the WW–WW system, while field peas and canola stubbles improved both the yield and stability of WW in the HRSW–WW system (Figure 2). Lentil and field pea stubbles in the WW–WW system, and lentil and soybean stubbles in the HRSW–WW system produced yields higher than average, though with increased variability.

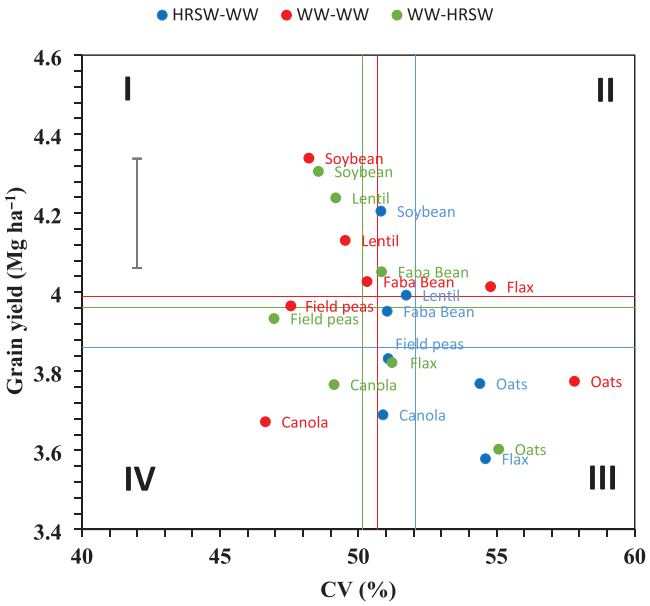


FIGURE 1 Biplots summarizing mean versus coefficient of variation (CV) for the wheat in the first wheat phase for grain yield data collected at environments across Canadian Prairies from 2019 to 2022. Error bar represents $LSD_{0.05}$ for rotational crop by rotation interaction. Group I: High mean, high stability; Group II: High mean, low stability; Group III: Low mean, low stability; Group IV: Low mean, high stability. The red, green, and blue horizontal lines represent the average grain yield of winter wheat (WW), WW, and hard red spring wheat (HRSW) in the WW–WW, WW–HRSW, and HRSW–WW systems, respectively. The green, red, and blue vertical lines represent the average CV of WW, WW, and HRSW in the WW–HRSW, WW–WW, and HRSW–WW systems, respectively.

For HRSW in the second wheat phase, lentil, field peas, and canola stubbles resulted in high and stable yields. Notably, canola stubbles maintained high and stable yields for both WW and HRSW in the second wheat phase, across the WW–WW, HRSW–WW, and WW–HRSW systems. Our results

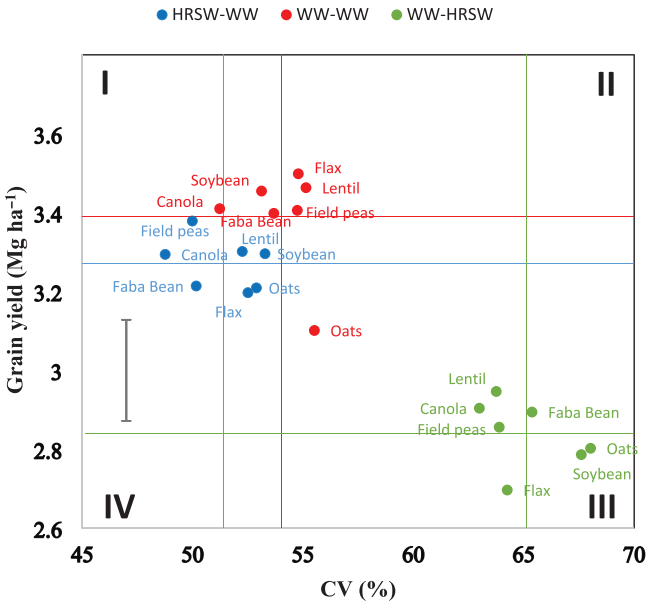


FIGURE 2 Biplots summarizing mean versus coefficient of variation (CV) for the wheat in the second wheat phase for grain yield data collected at environments across Canadian Prairies from 2019 to 2022. Error bar represents $LSD_{0.05}$ for rotational crop by rotation interaction. Group I: High mean, high stability; Group II: High mean, low stability; Group III: Low mean, low stability; Group IV: Low mean, high stability. The red, blue, and green horizontal lines represent the average grain yield of winter wheat (WW), WW, and hard red spring wheat (HRSW) in the WW–WW, HRSW–WW, and WW–HRSW systems, respectively. The blue, red, and green vertical lines represent the average CV of WW, WW, and HRSW in the HRSW–WW, WW–WW, and WW–HRSW systems, respectively.

suggest that soybean and lentil stubbles benefit WW production not only immediately but also positively impact yields in the second year following this rotational crop. Although canola is often considered the gold standard for WW in NGP due to its snow-trapping potential (Irvine et al., 2013), our research indicates that viable alternative cropping options exist. Research across multiple countries has shown that the soil following an annual crop legume often contains 30–60 kg N ha^{-1} more than after a cereal crop and this increased plant-available nitrogen is converted into increased cereal grain yield (Herridge et al., 1995). In addition to nitrogen enrichment, leguminous plants may benefit cereals in crop rotations by improving soil physical properties, reducing soil erosion, and suppressing weeds, insects, and diseases (Sarobol & Anderson, 1992). Moreover, legumes play a crucial role as a global source of high-quality food and feed, and they also help mitigate greenhouse gas emissions, releasing five to seven times less greenhouse gas per unit area compared to other crops worldwide (Stagnari et al., 2017). Canola stubble did not provide this advantage when WW followed immediately. However, in the second wheat phase, canola stubble contributed to higher and more stable yields for both WW and HRSW relative to other rotational crops. We previously observed a yield drag in the cereal phase of a canola-cereal-field peas rotation and attributed it to potential benefits for cereals when following a non-host of arbuscular mycorrhizal fungi (Beres et al., 2018b). The increased effectiveness of canola and the reduced impact of leguminous crops might explain the lack of significant differences in wheat grain yield among the rotational crops in the second wheat phase. The effect of canola on the succeeding crop in this study differs from Angus et al. (2015), who found that oilseeds had a relatively smaller effect on the second wheat crop compared to oats or grain legumes in Australia.

A PLS-AMMI biplot indicated that Indian Head 2019, Brandon 2020, and Lethbridge 2021 were characterized by high air temperatures, wettest and least stressful, and drought stress conditions, respectively (Figures 3 and 4). WW was responsive to field peas, lentil, soybean, and canola stubbles during the first wheat phase. Notably, WW yield on field peas stubble at Brandon 2020 was higher than on other rotational crops due to less stressful conditions at that site-year. No significant response of HRSW to rotational crops was observed, except for oats and faba bean, which showed greater HRSW yields at Lethbridge 2021 under drought conditions during the first wheat phase. In addition, HRSW yield on oat stubble was among the lowest at Brandon 2020.

During the second wheat phase, the combination of oats stubble with higher GDD led to higher WW yields at Brandon 2021 and Lethbridge 2022 in the HRSW–WW system, while flax stubble with increased precipitation contributed to higher WW yields at Brandon 2022 in the same system (Figure 4). Conversely, canola stubble resulted in among the lowest WW yields at Lethbridge 2021. In the WW–WW system, all rotational crop stubbles performed similarly for the second WW, except for canola and soybean, which resulted in lower WW yields at Lethbridge 2021 under drought conditions. Faba bean and soybean stubbles produced higher HRSW yields under drought conditions at Lethbridge 2021, while high air temperatures led to increased HRSW yield from field peas stubble at Indian Head 2019 within the WW–HRSW system.

3.2 | Wheat grain quality response to rotational crop and crop rotation

No differences in protein concentration or test weight were observed among rotational crops; however, protein concentration was influenced by crop rotation in the first wheat phase (Table 2). In the second wheat phase, rotational crops did not affect quality variables, while crop rotation continued to affect protein concentration (Table 3). Protein concentration was similar for WW in cereal rotational systems whether grown immediately or in the second year after

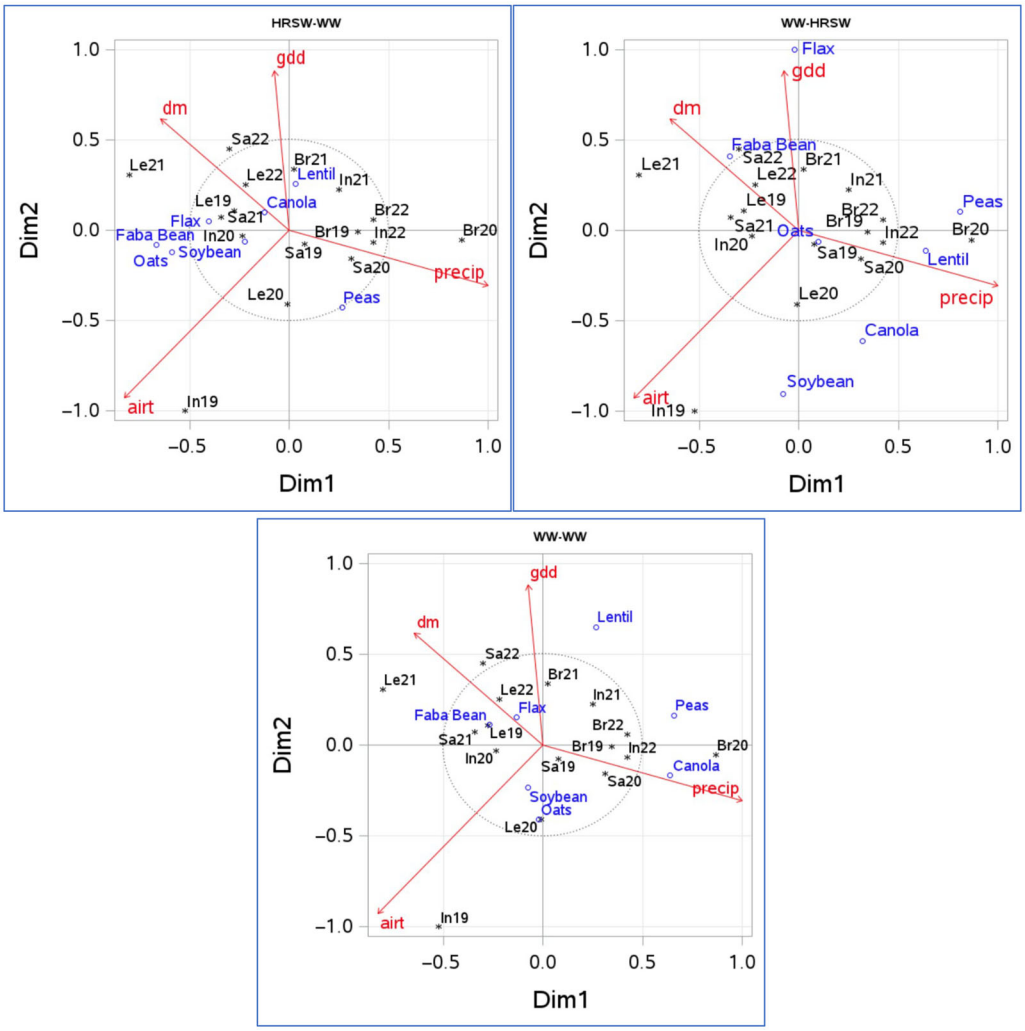


FIGURE 3 Partial least squares (PLS) and additive main effects and multiplicative interaction (AMMI) biplots for the first wheat grain yield of seven rotational crops, three crop rotations, and 12 site-years. Le, Sa, In, and Br represent Lethbridge, Saskatoon, Indian Head, and Brandon, respectively. Numbers 19, 20, 21, and 22 are growing seasons 2018–2019, 2019–2020, 2020–2021, and 2021–2022 for winter wheat, and 2019, 2020, 2021, and 2022 for spring wheat, respectively. Dm, gdd, precip, and airt denote drought stress, growing degree days, precipitation, and air temperature, respectively.

preceding crops, except that canola stubble produced lower protein concentration compared to faba bean stubble in the second year (Table 4). Similar to grain yield, WW protein concentration was particularly responsive when grown on field peas stubble. Canola stubble consistently resulted in the lowest WW protein concentration in both the first and second wheat phases. Arshad et al. (2002) reported that wheat immediately following canola in the Canadian Prairies had significantly lower protein content compared to the second wheat in a canola–wheat–wheat system, as well as the first and second wheat in field peas–wheat–wheat and fallow–wheat–wheat systems. Contrary to the grain yield responses, protein concentration of HRSW increased in the second wheat phase compared to the first, reflecting an inverse relationship between grain yield and protein concentration (Fast et al., 2023). Test weight was higher in the first wheat phase than in the second for both WW and HRSW. In the first wheat phase, test weight was lowest with oats, which is significantly lower than soybean and faba bean.

The biplot in Figure 5 indicate soybean and faba bean stubbles achieved superior and consistent protein concentrations for HRSW in the HRSW–WW system, lentil and faba bean stubbles for WW in the WW–HRSW system, and field peas, faba bean, and lentil stubbles for WW in the WW–WW system during the first wheat phase. In contrast, canola stubbles consistently resulted in highly variable protein concentrations for both WW and HRSW in the first wheat phase. Field peas stubble also produced variable protein concentrations for HRSW in the HRSW–WW system and WW in the WW–HRSW system.

In the second wheat phase, soybean, faba bean, and field peas stubbles, as well as field peas and oats stubbles, yielded

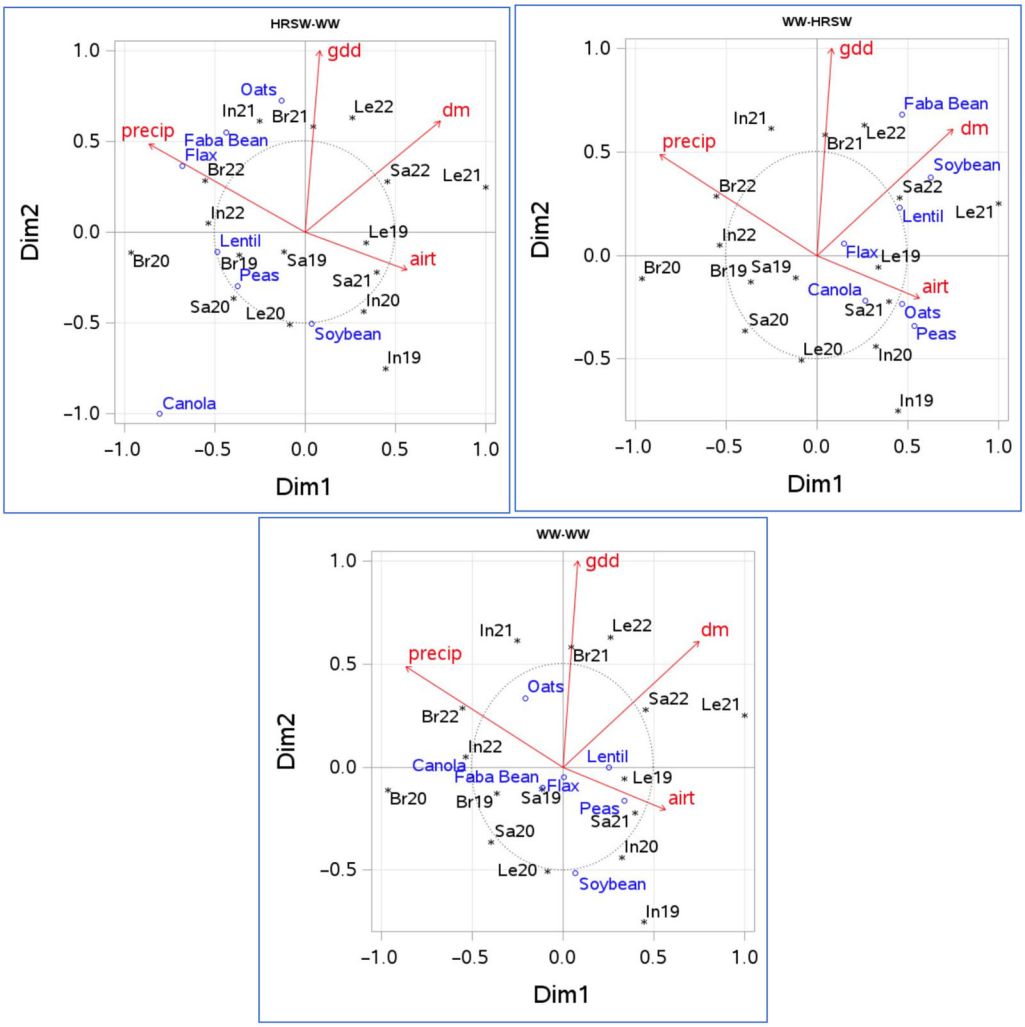


FIGURE 4 Partial least squares (PLS) and additive main effects and multiplicative interaction (AMMI) biplots for the second wheat grain yield of seven rotational crops, three crop rotations, and 15 site-years. Le, Sa, In, and Br represent Lethbridge, Saskatoon, Indian Head, and Brandon, respectively. Numbers 19, 20, 21, and 22 are growing seasons 2018–2019, 2019–2020, 2020–2021, and 2021–2022 for winter wheat, and 2019, 2020, 2021, and 2022 for spring wheat, respectively. Dm, gdd, precip, and airt denote drought stress, growing degree days, precipitation, and air temperature, respectively.

high and stable protein concentrations for WW and HRSW, respectively (Figure 6). Conversely, canola stubble, along with lentil, flax, and soybean stubbles, resulted in low and variable protein concentrations for WW and HRSW, respectively. Faba bean and oats stubbles produced high protein concentrations but with high variability for the second-year WW in the WW–WW system. Our results suggest that soybean and faba bean stubbles in the HRSW–WW system and field peas in the WW–WW system not only benefit wheat protein levels immediately but also positively impact protein concentrations in the second year following these crops. Previous research in both Western and Eastern Canada has shown a strong correlation between wheat protein concentration and soil nitrogen levels (Fast et al., 2023; Fowler, 2003; Subedi et al., 2007). The low and unstable protein concentrations associated with canola stubble may be due to canola's higher nitrogen uptake, which leaves less available nitrogen for the succeeding wheat phase (Kirkegaard et al., 1997). In contrast, leguminous crops can fix nitrogen and supply it to subsequent crops (Khakbazan et al., 2014), thereby enhancing protein accumulation in the following wheat phases.

3.3 | Interaction of environment and wheat yield and quality

For covariance estimates, site and site-by-treatment interactions were often statistically significant, with a few exceptions (Tables 2 and 3). Site covariance estimates for grain yield, 1000-kernel weight, plant density, head density, and test weight were greater (>80%) compared to other wheat

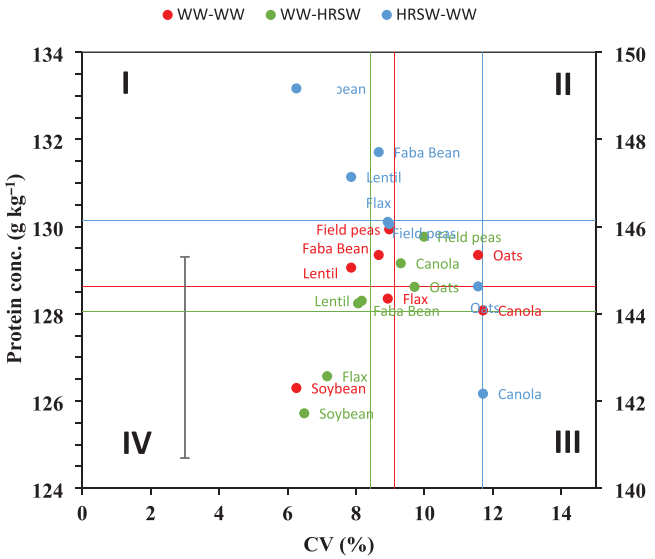


FIGURE 5 Biplots summarizing mean versus coefficient of variation (CV) for the wheat in the first wheat phase for protein concentration data collected at environments across Canadian Prairies from 2019 to 2022. Error bar represents $LSD_{0.05}$ for rotational crop by rotation interaction. Group I: High mean, high stability; Group II: High mean, low stability; Group III: Low mean, low stability; Group IV: Low mean, high stability. The blue, green, and red horizontal lines represent the average grain yield of hard red spring wheat (HRSW), winter wheat (WW), and WW in the HRSW–WW, WW–HRSW, and WW–WW systems, respectively. The blue, red, and green vertical lines represent the average CV of HRSW, WW, and WW in the HRSW–WW, WW–WW, and WW–HRSW systems, respectively.

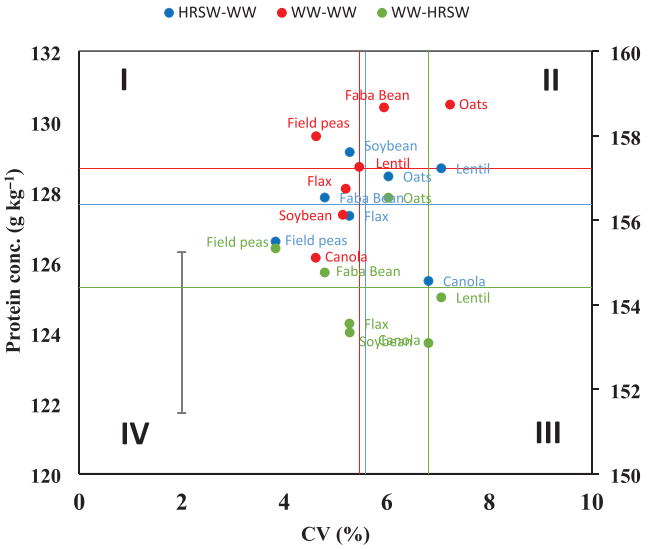


FIGURE 6 Biplots summarizing mean versus coefficient of variation (CV) for the wheat in the second wheat phase for protein concentration data collected at environments across Canadian Prairies from 2019 to 2022. Error bar represents $LSD_{0.05}$ for rotational crop by rotation interaction. Group I: High mean, high stability; Group II: High mean, low stability; Group III: Low mean, low stability; Group IV: Low mean, high stability. The red, blue, and green horizontal lines represent the average grain yield of winter wheat (WW), WW, and hard red spring wheat (HRSW) in the WW–WW, HRSW–WW, and WW–HRSW systems, respectively. The green, red, and blue vertical lines represent the average CV of HRSW, WW, and WW in the WW–HRSW, WW–WW, and HRSW–WW systems, respectively.

responses in the first wheat phase (Table 2). Higher site covariance estimates were observed for grain yield, 1000-kernel weight, plant density, and test weight compared to head density, protein concentration, and test weight in the second wheat phase (Table 3). In both the first and second wheat phases, the percentage of covariance accounted for by the site represented the majority of variation in all wheat responses, suggesting that these variables are highly dependent on the environment. Our research supports Angus et al. (2015), who reported that the persistence of rotational crop effects likely depends on seasonal conditions, being greatest in dry environments and more variable in moist and semi-arid environments in Australia. Variation associated with site-by-crop rotation interactions explained >20% of the covariance due to random effects for head per plant and protein concentration in the first wheat phase, and for head density, head per plant, and protein concentration in the second wheat phase (Tables 2 and 3). This suggests that when environmental conditions limit head development and protein potential, crop rotation can optimize wheat protein accumulation, which aligns with the fixed effect of rotation.

3.4 | In-season growth response to rotational crop and crop rotation

The analysis of in-season growth responses, NDVI, LAI, and Chl index revealed that LAI and Chl index in the first wheat phase and LAI in the second wheat phase varied among the rotational crops (Table 5). Crop rotation affected all three in-season growth responses in the first wheat phase, as well as NDVI and Chl index in the second wheat phase. The significant site, site by rotational crop, and site by crop rotation effects were observed for all the in-season growth responses, except for a site-by-rotational crop effect on NDVI in the second wheat phase. This suggests that, beyond the effects of rotational crop and crop sequencing, the growing environment plays a crucial role in wheat performance.

Mean estimates showed that lentil stubble resulted in the highest NDVI in the first wheat phase compared to other rotational crops (Table 5). In the second wheat phase, soybean, lentil, faba bean, and canola produced higher NDVI than field peas, flax, and oats. Lentil also had the highest LAI values of the first wheat phase, while flax had the lowest, with other rotational crops falling in between. In the second wheat phase, lentil and soybean provided higher LAI than other rotational

TABLE 5 Analysis of variance and means for in-season wheat growth as influenced by rotational crops and crop rotation across the Canadian Prairies from 2019 to 2022.

	First wheat phase			Second wheat phase		
	NDVI	LAI	Chl index	NDVI	LAI	Chl index
	p-values					
RC	0.086	0.014**	0.025*	0.644	<0.001***	0.283
CR	<0.001***	<0.001***	0.026*	<0.001***	0.410	<0.001***
RC × CR	0.499	0.387	0.836	0.391	0.896	0.983
Site	<0.001***	<0.001***	0.004**	<0.001***	<0.001***	<0.001***
Site × RC	<0.001***	<0.001***	<0.001***	0.850	0.008**	0.004**
Site × CR	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Site × RC × CR	0.625	0.363	0.728	0.563	0.927	0.996
	Means					
RC						
Soybean	0.51	1.27bc	395.8ab	0.56	1.58ab	381.3
Lentil	0.53	1.38a	416.5a	0.56	1.60a	387.1
Field peas	0.51	1.33ab	401.3ab	0.55	1.48bcd	367.9
Faba bean	0.51	1.26bc	407.9ab	0.56	1.53abc	387.4
Canola	0.51	1.23bc	384.0b	0.56	1.42d	355.3
Flax	0.51	1.22c	418.6a	0.55	1.47cd	372.3
Oats	0.51	1.24bc	385.1b	0.55	1.40d	375.7
CR						
HRSW-WW	0.53a	1.36a	411.4a	0.53c	1.48	326.6c
WW-HRSW	0.50b	1.22b	389.2c	0.59a	1.49	439.9a
WW-WW	0.51b	1.25b	403.4bc	0.55b	1.53	359.3b

Abbreviations: Chl, chlorophyll; CR, crop rotation; HRSW, hard red spring wheat; LAI, leaf area index; NDVI, Normalized Difference Vegetation Index; RC, rotational crop; WW, winter wheat.

*, **, and *** denote significant effects at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively. Means followed by the same letter are not significantly different ($p < 0.05$).

crops. The Chl index was highest with lentil and flax in the first wheat phase, lowest with canola and oats, and intermediate with other rotational crops. Lentil, soybean, and faba bean had higher Chl indexes in the second wheat phase compared to other rotational crops.

Seedling vigor in the wheat phases ranged from 2 to 5 (Table 6). The vigor of both the first and second wheat phases on leguminous stubbles had a great proportion of high late-season (Feekes 8) vigor values, 4 and 5, compared to non-leguminous stubbles, which aligns with the trends observed in NDVI, LAI, and the Chl index. At Feekes 8, WW was more vigorous than HRSW in both the first and second wheat phases too, explaining the higher grain yield in WW compared to HRSW.

Overall, leguminous stubbles, especially lentil, resulted in superior in-season growth compared to canola, flax, and oats. Previous research in the Canadian Prairies indicates that leguminous crops fix nitrogen and enhance mineral nitrogen availability (Khakbazan et al., 2014). Studies in Europe also show a strong correlation between wheat NDVI, LAI, and Chl index at late growth stages and grain yield (Morgounov et al., 2014; Petcu et al., 2003). The higher yields observed in wheat phases following leguminous stubbles are attributed to the improved in-season growth these crops facilitate. These findings align with Agenbag (2012) and Peoples et al. (2017), who reported that leguminous crops enhance plant-available nitrogen and promote more vigorous wheat growth in South Africa and Australia.

In the first wheat phase, HRSW exhibited higher NDVI, LAI, and Chl index than WW. However, WW showed improved NDVI, LAI, and Chl index relative to HRSW in the second wheat phase, particularly the WW following HRSW. This explains the observed yield drag in HRSW compared to WW in the second wheat phase.

4 | CONCLUSIONS

This study investigated the impact of different rotational crops on subsequent WW and HRSW crops in WW–WW, HRSW–WW, and WW–HRSW systems. While canola is often considered as the optimal rotational crop for WW due to its snow-trapping ability, our results highlighted several viable alternatives. Soybean and lentil consistently outperformed

TABLE 6 Cumulative probabilities of each vigor level (2, 3, 4, and 5) across different rotational crops and crop rotation across the Canadian Prairies from 2019 to 2022.

		Early-season vigor				Late-season vigor			
Crop rotation	**Rotational crop**	**2**	**3**	**4**	**5**	**2**	**3**	**4**	**5**
First wheat phase	Soybean	0.337	0.558	0.097	0.008	0.022	0.455	0.484	0.039
	Lentil	0.207	0.607	0.170	0.016	0.009	0.255	0.642	0.095
	Field peas	0.193	0.608	0.182	0.017	0.007	0.223	0.659	0.111
	Faba Bean	0.319	0.568	0.104	0.009	0.014	0.350	0.575	0.061
	Canola	0.200	0.608	0.176	0.016	0.017	0.399	0.534	0.050
	Flax	0.113	0.569	0.287	0.032	0.010	0.288	0.621	0.081
	Oats	0.171	0.605	0.204	0.020	0.032	0.546	0.396	0.027
Second wheat phase	Soybean	0.169	0.455	0.364	0.012	0.025	0.142	0.700	0.132
	Lentil	0.175	0.460	0.354	0.011	0.022	0.128	0.702	0.148
	Field peas	0.202	0.472	0.316	0.010	0.026	0.147	0.699	0.128
	Faba Bean	0.177	0.461	0.351	0.011	0.030	0.164	0.693	0.113
	Canola	0.182	0.463	0.344	0.011	0.033	0.178	0.686	0.103
	Flax	0.195	0.470	0.326	0.010	0.030	0.165	0.693	0.113
	Oats	0.292	0.479	0.223	0.006	0.043	0.218	0.659	0.080
First wheat phase	HRSW-WW	0.473	0.465	0.058	0.005	0.074	0.694	0.221	0.011
	WW-HRSW	0.137	0.590	0.248	0.026	0.006	0.202	0.667	0.124
	WW-WW	0.119	0.575	0.277	0.030	0.005	0.180	0.673	0.141
Second wheat phase	HRSW-WW	0.084	0.344	0.546	0.026	0.008	0.050	0.609	0.333
	WW-HRSW	0.242	0.481	0.269	0.008	0.204	0.464	0.317	0.015
	WW-WW	0.334	0.470	0.191	0.005	0.013	0.083	0.680	0.224

Abbreviations: HRSW, hard red spring wheat; WW, winter wheat.

canola in terms of grain yield and protein concentration for WW when used as preceding crops. In the second year following lentil and field peas, WW grain yields were similar to those following canola, but with higher protein concentrations. Beyond agronomic advantages, these alternatives enhance cropping system diversity. The inclusion of leguminous crops can improve soil health and fertility, leading to better wheat performance. This contributes to the overall sustainability and productivity of the cropping system. Additionally, rotational crops with biological nitrogen fixation can reduce the need for synthetic nitrogen fertilizers, thereby lowering the environmental impact of farming practices.

In terms of crop sequencing, WW yield was greater than HRSW not only in the first year, but also in the second year after rotational crops. This suggests that WW may be more responsive to the benefits of preceding rotational crops, which could enhance the resilience of diverse cropping systems. Overall, our observations underscore the potential of alternative rotational crops to improve wheat production while supporting sustainable agricultural practices.

AUTHOR CONTRIBUTIONS

Zhijie Wang: Data curation; formal analysis; validation; writing—original draft; writing—review and editing. **F. Craig Stevenson**: Formal analysis; methodology; software; writing—review and editing. **Ramona M. Mohr**: Investigation; methodology; writing—review and editing. **Christian Willenborg**: Investigation; methodology; writing—review and editing. **William E. May**: Investigation; methodology; writing—review and editing. **Brian L. Beres**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

This research was funded by Saskatchewan Winter Cereals Development Commission (now amalgamated with the Saskatchewan Wheat Development Commission), Canadian Wheat Research Coalition, Alberta Grains, and the Western Grains Research Foundation with additional funding leveraged from Agriculture and Agri-Food Canada's Canadian Agricultural Partnership's AgriScience Program, a federal, provincial, territorial initiative. This work is not possible without the awesome technical teams at each location: Lethbridge team—Ryan Dyck, Steve Simmill, Warren Taylor, and Kaitlyn Heidinger; Brandon team—Gordon Finlay; Indian Head team—Rebecca Davies and Orla Willoughby; and Saskatoon team—Aaron Gerein.

Open Access funding provided by the Gouvernement du Canada Agriculture et Agroalimentaire Canada library.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Agenbag, G. (2012). Growth, yield and grain protein content of wheat (*Triticum aestivum* L.) in response to nitrogen fertiliser rates, crop rotation and soil tillage. *South African Journal of Plant and Soil*, *29*(2), 73–79. https://doi.org/10.1080/02571862.2012.716457

Angus, J., Kirkegaard, J., Hunt, J., Ryan, M., Ohlander, L., & Peoples, M. (2015). Break crops and rotations for wheat. *Crop and Pasture Science*, *66*, 523–552. https://doi.org/10.1071/CP14252

Anonymous. (2019). *Working with binary and multinomial data in GLIMMIX*. Agricultural Statistics. https://agstats.ca/

Arshad, M., Gill, K., & Izaurralde, R. (1998). Wheat production, weed population and soil properties subsequent to 20 years of sod as affected by crop rotation and tillage. *Journal of Sustainable Agriculture*, *12*(2–3), 131–154. https://doi.org/10.1300/j064v12n02_10

Arshad, M., Soon, Y., & Azooz, R. (2002). Modified no-till and crop sequence effects on spring wheat production in northern Alberta, Canada. *Soil and Tillage Research*, *65*(1), 29–36. https://doi.org/10.1016/s0167-1987(01)00272-0

Beck, D. P. (1992). Yield and nitrogen fixation of chickpea cultivars in response to inoculation with selected rhizobial strains. *Agronomy Journal*, *84*(3), 510–516. https://doi.org/10.2134/agronj1992.00021962008400030029x

Beres, B. L., Graf, R. J., Irvine, R. B., O'Donovan, J. T., Harker, K. N., Johnson, E. N., Brandt, S., Hao, X., Thomas, B. W., & Turkington, T. K. (2018a). Enhanced nitrogen management strategies for winter wheat production in the Canadian prairies. *Canadian Journal of Plant Science*, *98*(3), 683–702. https://doi.org/10.1139/cjps-2017-0319

Beres, B. L., Lupwayi, N., Larney, F., Ellert, B., Smith, E., Turkington, T., Pageau, D., Semagn, K., & Wang, Z. (2018b). Rotational diversity effects in a triticale-based cropping system. *Cereal Research Communications*, *46*(4), 717–728. https://doi.org/10.1556/0806.46.2018.051

Beres, B. L., Rahmani, E., Clarke, J. M., Grassini, P., Pozniak, C. J., Geddes, C. M., Porker, K. D., May, W. E., & Ransom, J. K. (2020). A systematic review of durum wheat: Enhancing production systems by exploring genotype, environment, and management (G × E × M) synergies. *Frontiers in Plant Science*, *11*, 568657. https://doi.org/10.3389/fpls.2020.568657

Crossa, J., Vargas, M., Cossani, C. M., Alvarado, G., Burgueño, J., Mathews, K. L., & Reynolds, M. P. (2015). Evaluation and interpretation of interactions. *Agronomy Journal*, *107*(2), 736–747. https://doi.org/10.2134/agronj2012.0491

Cuthbert, R. D., DePauw, R., Knox, R., Singh, A. K., McCallum, B., & Fetch, T. (2018). AAC Viewfield hard red spring wheat. *Canadian Journal of Plant Science*, *99*(1), 102–110. https://doi.org/10.1139/cjps-2018-0147

Domitruk, D., Duggan, B., & Fowler, D. (2000). Soil water use, biomass accumulation and grain yield of no-till winter wheat on the Canadian prairies. *Canadian Journal of Plant Science*, *80*(4), 729–738. https://doi.org/10.4141/p00-004

Entz, M. H., Baron, V. S., Carr, P. M., Meyer, D. W., Smith, S. R., Jr., & McCaughey, W. P. (2002). Potential of forages to diversify cropping systems in the northern Great Plains. *Agronomy Journal*, *94*(2), 240–250. https://doi.org/10.2134/agronj2002.2400

Entz, M. H., & Fowler, D. B. (1991). Agronomic performance of winter versus spring wheat. *Agronomy Journal*, *83*(3), 527–532. https://doi.org/10.2134/agronj1991.00021962008300030002x

Fast, A., Strydhorst, S., Wang, Z., Hernandez-Ramirez, G., Hao, X., Semach, G., Thompson, L., Holzapfel, C., Enns, J., Spaner, D., & Beres, B. L. (2023). Integrating enhanced efficiency fertilizers and nitrogen rates to improve Canada Western Red Spring wheat production in the Canadian prairies. *Canadian Journal of Plant Science*, *104*, 144–160. https://doi.org/10.1139/cjps-2023-0095

Fowler, D. (2003). Crop nitrogen demand and grain protein concentration of spring and winter wheat. *Agronomy Journal*, *95*(2), 260–265. https://doi.org/10.2134/agronj2003.2600

Francis, T. R., & Kannenberg, L. W. (1978). Yield stability studies in short-season maize. I. A descriptive method for grouping genotypes. *Canadian Journal of Plant Science*, *58*(4), 1028–1034. https://doi.org/10.4141/cjps78-157

Gaudin, A. C. M., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One*, *10*, e0113261. https://doi.org/10.1371/journal.pone.0113261

Graf, R., Beres, B., Gaudet, D., Thomas, J., & Butts, R. (2016). AAC Wildfire hard red winter wheat. *Canadian Journal of Plant Science*, *97*(1), 183–191. https://doi.org/10.1139/cjps-2016-0155

Groeneveld, M., Grunwald, D., Piepho, H.-P., & Koch, H.-J. (2024). Crop rotation and sowing date effects on yield of winter wheat. *The Journal of Agricultural Science*, *162*(2), 139–149. https://doi.org/10.1017/S0021859624000261

Herridge, D., Marcellos, H., Felton, W., & Peoples, M. (1995). Legume N2 fixation—An efficient source of nitrogen for cereal production. In *Nuclear methods in soil-plant aspects of sustainable agriculture, IAEA-TECDOC-785* (pp. 77–89). IAEA. https://inis.iaea.org/records/z4m5y-msq61#page=74

Irvine, R. B., Lafond, G. P., May, W., Kutcher, H. R., Clayton, G. W., Harker, K. N., Turkington, T. K., & Beres, B. L. (2013). Stubble options for winter wheat in the black soil zone of western Canada. *Canadian Journal of Plant Science*, *93*(2), 261–270. https://doi.org/10.4141/cjps2012-198

Jacques, C., Salon, C., Barnard, R. L., Vernoud, V., & Prudent, M. (2021). Drought stress memory at the plant cycle level: A review. *Plants*, *10*(9), 1873. https://doi.org/10.3390/plants10091873

Khakbazan, M., Grant, C. A., Huang, J., Smith, E. G., O'Donovan, J. T., Blackshaw, R. E., Harker, K. N., Lafond, G. P., Johnson, E. N., & Gan, Y. (2014). Economic effects of preceding crops and nitrogen application on canola and subsequent barley. *Agronomy Journal*, *106*(6), 2055–2066. https://doi.org/10.2134/agronj14.0253

Kirkegaard, J., Hocking, P., Angus, J., Howe, G., & Gardner, P. (1997). Comparison of canola, Indian mustard and Linola in two contrasting environments. II. Break-crop and nitrogen effects on subsequent wheat crops. *Field Crops Research*, *52*(1–2), 179–191. https://doi.org/10.1016/s0378-4290(96)01057-x

Kirkegaard, J., Simpfendorfer, S., Holland, J., Bambach, R., Moore, K., & Rebetzke, G. (2004). Effect of previous crops on crown rot and yield of durum and bread wheat in northern NSW. *Australian Jour-*

nal of Agricultural Research, *55*(3), 321–334. https://doi.org/10.1071/ar03178

Krupinsky, J. M., Tanaka, D. L., Merrill, S. D., Liebig, M. A., & Hanson, J. D. (2006). Crop sequence effects of 10 crops in the northern Great Plains. *Agricultural Systems*, *88*, 227–254. https://doi.org/10.1016/j.agsy.2005.03.011

Kumar, K., & Goh, K. M. (2002). Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. *European Journal of Agronomy*, *16*(4), 295–308. https://doi.org/10.1016/s1161-0301(01)00133-2

Large, E. C. (1954). Growth stages in cereals illustration of the Feekes scale. *Plant Pathology*, *3*(4), 128–129. https://doi.org/10.1111/j.1365-3059.1954.tb00716.x

Littell, R. C., Milliken, G. A., Stroup, W. W., & Wolfinger, R. D. (2006). *SAS® system for mixed models* (2nd ed.). SAS Institute Inc.

Lollato, R. P., & Edwards, J. T. (2015). Maximum attainable wheat yield and resource-use efficiency in the southern Great Plains. *Crop Science*, *55*(6), 2863–2876. https://doi.org/10.2135/cropsci2015.04.0215

Lupwayi, N. Z., Rice, W. A., & Clayton, G. W. (1998). Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. *Soil Biology and Biochemistry*, *30*(13), 1733–1741. https://doi.org/10.1016/S0038-0717(98)00025-X

Lupwayi, N. Z., & Soon, Y. K. (2016). Nitrogen-related rotational effects of legume crops on three consecutive subsequent crops. *Soil Science Society of America Journal*, *80*(2), 306–316. https://doi.org/10.2136/sssaj2015.08.0299

Mooleki, S., Slinkard, A., & van Kessel, C. (1998). *Landscape-scale variation in yield and N uptake of the second wheat crop in a lentil-wheat-wheat rotation*. Soils and Crops Workshop.

Morgounov, A., Gummadov, N., BELEN, S., KAYA, Y., Keser, M., & Mursalova, J. (2014). Association of digital photo parameters and NDVI with winter wheat grain yield in variable environments. *Turkish Journal of Agriculture and Forestry*, *38*(5), 624–632. https://doi.org/10.3906/tar-1312-90

Peoples, M. B., Swan, A. D., Goward, L., Kirkegaard, J. A., Hunt, J. R., Li, G. D., Schwenke, G. D., Herridge, D. F., Moodie, M., & Wilhelm, N. (2017). Soil mineral nitrogen benefits derived from legumes and comparisons of the apparent recovery of legume or fertiliser nitrogen by wheat. *Soil Research*, *55*(6), 600–615. https://doi.org/10.1071/SR16330

Petcu, E., Petcu, G., Lazăr, C., & Vintilă, R. (2003). Relationship between leaf area index, biomass and winter wheat yield obtained at Fundulea, under conditions of 2001 year. *Romanian Agricultural Research*, *19–20*, 21–29. https://www.academia.edu/download/39514576/RELATIONSHIP_BETWEEN_LEAF_AREA_INDEX_BIO20151028-25080-gp20e8.pdf

Piepho, H.-P. (1999). Stability analysis using the SAS system. *Agronomy Journal*, *91*(1), 154–160. https://doi.org/10.2134/agronj1999.00021962009100010024x

Rashid, U., Yasmin, H., Hassan, M. N., Naz, R., Nosheen, A., Sajjad, M., Ilyas, N., Keyani, R., Jabeen, Z., Mumtaz, S., Alyemeni, M. N., & Ahmad, P. (2022). Drought-tolerant Bacillus megaterium isolated from semi-arid conditions induces systemic tolerance of wheat under drought conditions. *Plant Cell Reports*, *41*(3), 549–569. https://doi.org/10.1007/s00299-020-02640-x

San Martín, C., Long, D. S., Gourlie, J. A., & Barroso, J. (2019). Spring crops in three year rotations reduce weed pressure in winter wheat. *Field Crops Research*, *233*, 12–20. https://doi.org/10.1016/j.fcr.2018.12.017

Sarobol, E., & Anderson, I. (1992). Improving yield of corn–soybean rotation: Role of allelopathy. In *Allelopathy: Basic and applied aspects* (pp. 87–100). Springer. https://link.springer.com/chapter/10.1007/978-94-011-2376-1_7

SAS Institute. (2023). *SAS/STAT® 15.3 user's guide*. SAS Institute Inc.

Seibutis, V., & Deveikyte, I. (2008). Efficiency of short crop rotations on the yields and quality of winter wheat grain. *Feeds and Feed Production*, *62*, 219–225. https://fri-journal.com/index.php/journal/article/view/1205

Soon, Y., & Arshad, M. (2004). Contribution of di-nitrogen fixation by pea to the productivity and N budget of a wheat-based cropping system. *The Journal of Agricultural Science*, *142*(6), 629–637. https://doi.org/10.1017/s002185960500482x

Stagnari, F., Maggio, A., Galieni, A., & Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: An overview. *Chemical and Biological Technologies in Agriculture*, *4*, Article 2. https://doi.org/10.1186/s40538-016-0085-1

Stroup, W. W. (2012). *Generalized linear mixed models: Modern concepts, methods and applications*. CRC Press. https://books.google.ca/books?hl=en&lr=&id=GcGrySpkXRMC&oi=fnd&pg=PP1&dq=Generalized+linear+mixed+models:+modern+concepts,+methods+and+applications&ots=jXXZqzdf_U&sig=2xizD1UxyOCo16O3Fe7W-4fFxpQ#v=onepage&q=Generalized%20linear%20mixed%20models%3A%20modern%20concepts%2C%20methods%20and%20applications&f=false

Subedi, K., Ma, B., & Xue, A. (2007). Planting date and nitrogen effects on Fusarium head blight and leaf spotting diseases in spring wheat. *Agronomy Journal*, *99*(1), 113–121. https://doi.org/10.2134/agronj2006.0171

Thorup-Kristensen, K., Salmerón Cortasa, M., & Loges, R. (2009). Winter wheat roots grow twice as deep as spring wheat roots, is this important for N uptake and N leaching losses? *Plant and Soil*, *322*, 101–114. https://doi.org/10.1007/s11104-009-9898-z

Wang, Z., Subedi, M., Mohr, R., Geddes, C. M., Aboukhaddour, R., Willenborg, C. J., Tidemann, B. D., Turkington, T. K., Kubota, H., & Beres, B. L. (2024). Effects of reduced pesticide use on winter wheat production in the Canadian Prairies. *Canadian Journal of Plant Science*, *104*, 582–594. https://doi.org/10.1139/cjps-2024-0043

Zentner, R., Campbell, C., Biederbeck, V., Miller, P., Selles, F., & Fernandez, M. (2001). In search of a sustainable cropping system for the semiarid Canadian prairies. *Journal of Sustainable Agriculture*, *18*(2–3), 117–136. https://doi.org/10.1300/j064v18n02_10

How to cite this article: Wang, Z., Stevenson, F. C., Mohr, R. M., Willenborg, C., May, W. E., & Beres, B. L. (2025). Immediate and second-year effects of preceding crops on wheat production in the Northern Great Plains. *Crop Science*, *65*, e70047. https://doi.org/10.1002/csc2.70047