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Diversifying cropping systems enhances productivity, stability, and nitrogen use efficiency

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Abstract

Long-term field experiments are useful for determining cropping system productivity, stability, and resource use efficiency. With 12 yr (2004–2015) of data from five cropping systems on a long-term experiment (> 30 yr) under semiarid conditions in Saskatchewan, Canada, a systems-approach was used to compare grain and protein yield, stability, nitrogen (N) dynamics, N fertilizer ($FUE_{G,P}$), and available N use efficiency ($NUE_{G,P}$) for grain and protein. Annualized grain and protein yields for wheat (*Triticum aestivum* L.)-canola (*Brassica napus* L.)-wheat-field pea (*Pisum sativum* L.; W-C-W-P) were 2244 and 372 kg ha^{-1}, respectively, 14 to 38% and 33 to 66% higher, respectively, than continuous wheat (ContW), summer fallow-wheat-wheat-wheat (F-W-W-W), F-W-W, and lentil (*Lens culinaris* Medik) green manure-wheat-wheat (GM-W-W). Fallow systems were the most stable, but less productive and well-adapted to low-yielding conditions, while GM-W-W was the least stable and poorly adapted. The ContW had below-average stability and was better suited to high-yielding conditions for grain. The W-C-W-P consistently produced above-average yields, and was best suited for high-yielding conditions for grain and protein. The ContW and W-C-W-P had the highest NUE_G (26.4 g kg^{-1}) and NUE_P (4.1 g kg^{-1}), respectively, with GM-W-W having the lowest (18.1 and 2.7 g kg^{-1}); FUE was the reverse of NUE. This long-term study showed that diversified cropping systems that include pulses can more consistently produce higher grain and protein yields, regardless of growing conditions, than most other systems with lower N fertilizer inputs, thereby potentially reducing the negative environmental consequences associated with N fertilizer application.

Abbreviations: ANM, apparent in-season net nitrogen mineralization; ContW, continuous wheat; FUE, nitrogen fertilizer use efficiency; F-W-W, summer fallow-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; GM, green manure; GM-W-W, lentil green manure-wheat-wheat; GSP, growing season precipitation; NUE, available nitrogen use efficiency; PET, potential evapotranspiration; SOM, soil organic matter; W-C-W-P, wheat-canola-wheat-field.

1 | INTRODUCTION

World population is expected to reach about 9 billion by 2050, with a corresponding rise in global food demand (Godfray et al., 2010; Lutz & Kc, 2010) requiring 100 to 110% increases in crop production (Tilman, Balzer, Hill, & Befort, 2011). Meeting the demand is a significant challenge, particularly as the availability of arable and fertile land for farming is decreasing due to urbanization and other industrial development. Moreover, society expects food production to be more sustainable, with little or no negative consequences to the environment (Jensen et al., 2012). Climate change and climate unpredictability may pose further threats to sustainable food production systems as climatic conditions have profound effects, negative and positive, on cropping system productivity, stability, and resource use efficiency (Congreves et al., 2016; Gaudin et al., 2015). Hence, food security, sustainability, and stability are major concerns at the local, regional, national, and global scales.

Until recent decades, crop production in the semiarid region of the Northern Great Plains of North America was predominantly a spring wheat (*Triticum aestivum* L.)–summer fallow based rotation (Archer, Liebig, Tanaka, & Pokharel, 2018; Campbell, Zentner, Janzen, & Bowren, 1990; Grant, Peterson, & Campbell, 2002; MacWilliam, Wismer, & Kulshreshtha, 2014; Tanaka, Lyon, Miller, Merrill, & McConkey, 2010). Summer fallow is practiced to conserve soil moisture, boost soil N supply for crops grown in the subsequent growing season, and control weeds to some extent (Campbell et al., 2008; Grant et al., 2002; McConkey, Campbell, Zentner, Peru, & Vandenbygaart, 2012; Tanaka et al., 2010), since water and N availability are the two most limiting factors for crop production in the semiarid region (Campbell et al., 2007b; Kröbel et al., 2012). However, frequent summer-fallowing has resulted in soil erosion (Hansen et al., 2017; Sainju, Caesar-Tonthat, Lenssen, Evans, & Kolberg, 2009; Sharratt, Wendling, & Feng, 2010), loss of soil organic matter (SOM; Campbell et al., 2005; Janzen et al., 1998; Lemke et al., 2012; Maillard, McConkey, St. Luce, Angers, & Fan, 2018), and N leaching (Campbell et al., 2006). In fact, summer fallow is often regarded as the single most destructive agricultural soil management practice (Miller et al., 2015), as the land is left bare. Although the stubble of the previous crop is left standing during the fallow period in no-till soils, there is less soil coverage and carbon input during the fallow phase as compared to a crop phase. Therefore, it is a positive development that land under summer fallow in the Canadian prairies decreased by 86% in 2016 compared to 1996 (Statistics Canada, 2018). This decline is linked to technological advances in farming practices including direct seeding and conservation agriculture, stubble management for snow trapping, improved pesticides for weeds, disease and insect control, diversified and continuous cropping, and crop varietal improvements (Archer et al., 2018; Smith, Zentner, Campbell, Lemke, & Brandt, 2017; Zentner et al., 2006).

Core Ideas

- Long-term studies reliably assess stability and resource use efficiency.
- Diversified crop rotations produce more than cereal or fallow systems.
- NUE is higher in continuous than fallow systems.
- Green manure systems are highly vulnerable in semiarid environments.
- Fallow systems are more stable but less productive than continuous cropping systems.

While growing cereals in monoculture is one means of increasing cropping intensity to enhance total grain production, these systems are heavily dependent on synthetic N fertilizer application (Gan et al., 2014, 2015; Kröbel et al., 2012), and high pesticide use (Fernandez, Wang, Cutforth, & Lemke, 2016; Kirkegaard & Ryan, 2014). Nitrogen fertilizer is usually the largest energy input and cost of production in this region (Gan et al., 2014; Zentner et al., 2006), and the high application rates may result in negative environmental consequences, such as increased greenhouse gas emissions and threats to soil and water quality. Therefore, economic, environmental, and social pressures are challenging the agricultural sector to reduce its dependence on synthetic N fertilizers. Improving N use efficiency is one of the primary goals in the agricultural sector. Diversifying crop rotations with annual pulses is regarded as a more sustainable alternative to summer fallow and monoculture systems (Gan et al., 2015). Pulses can meet some or all of their N requirements through biological N fixation, and provide N to subsequent crops, thus lowering overall synthetic N fertilizer use (Gan et al., 2014; St. Luce et al., 2015, 2016a). Pulses can also break pest and disease cycles (Kirkegaard & Ryan, 2014; Stevenson & van Kessel, 1996). In addition, the shallow root systems of pulses (Gan, Liu, Cutforth, Wang, & Ford, 2011) can conserve precious soil water for subsequent, deeper-rooted crops in the rotation (Wang, Gan, Hamel, Lemke, & McDonald, 2012).

It is expected that climate change in this semiarid region will increase mean annual temperatures, however, precipitation change is rather unclear (Li et al., 2018; Qian et al., 2013). While a further extension of the growing season is forecasted for the future (Qian et al., 2013), hotter and drier conditions can lead to higher frequency and intensity of drought and water stress, and may influence pest and disease incidence and severity. Thus, biotic and abiotic factors may have more profound influences on sustainability of crop production in the future. The concept of stability was proposed as a means of assessing the sustainability of crop production systems.

According to Urruty, Tailliez-Lefebvre, and Huyghe (2016), stability of crop production systems reflects the consistency of crop production or yield over long periods of time or across various spatial environments. Therefore, yield stability can serve as a measure of the level of yield sensitivity to environmental factors (Berzsenyi, Győrffy, & Lap, 2000; Liu et al., 2019). Development and adoption of productive, efficient, sustainable, and profitable cropping systems require a thorough evaluation of several years of experimentation. Long-term cropping experiments are ideally suited in such cases, and can aid in making science-based decisions for developing best management practices (Johnston & Poulton, 2018).

The objective of this study was to use a system-approach to examine the effect of summer fallow frequency, summer fallow replacement with annual green manure (GM), cereal monoculture, and diversified cropping with cereals, oilseeds, and pulses on total grain and protein yield, stability, adaptability, and N use efficiency over a 12-yr period under semiarid conditions.

2 | MATERIALS AND METHODS

2.1 | Site and experimental description

This study was initiated in 1987 at the Agriculture and Agri-Food Canada Research and Development Centre at Swift Current, SK (50° 17′N, 107° 48′W, and elevation of 825 m) on a Swinton loam, classified as an Aridic Haplustoll (Soil Survey Staff, 2014; Orthic Brown Chernozem, Ayers, Acton, & Ellis, 1985). Details of the experimental design and plot management were reported previously (Smith et al., 2017; Zentner et al., 2003), and thus only a brief summary will be provided here. The soil has a pH of 6.5, and contains 343, 484, and 174 g kg^{-1} of sand, silt and clay, respectively, in the 0- to 15-cm depth, with an initial organic carbon and total N concentration of 18 and 1.8 g kg^{-1}, respectively, in the 0- to 7.5-cm depth. The site was continuously cropped to spring wheat (*Triticum aestivum* L.) with only phosphorus fertilizer applied for 3 yr prior to the start of the experiment with no N fertilizer applied.

Nine crop rotations were initially established: four 3-yr, one 4-yr, one continuous wheat, two flexible crop rotations, and a perennial grass system. In 2003, two of the original crop rotations were discontinued, and the plots were randomly assigned to a 4-yr diversified crop rotation of cereal-oilseed-cereal-pulse. This study is focused on five crop rotations in place since 2003: fallow-wheat-wheat (F-W-W; where F refers to summer fallow and W refers to Canada Western Hard Red Spring Wheat), lentil (*Lens culinaris* Medik) green manure-wheat-wheat (GM-W-W; where GM refers to lentil green manure), fallow-wheat-wheat-wheat (F-W-W-W), continuous wheat (ContW) and wheat-canola (*Brassica napus* L.)-wheat-field pea (*Pisum sativum* L.; W-C-W-P). Each crop or fallow in the rotation is referred to as a phase. For example, W-C-W-P had four phases, GM-W-W had three phases, while ContW had one phase. All phases of each rotation were present every year, and each rotation was cycled on its assigned plots (Smith et al., 2017; Zentner et al., 2006). Plots were 15 m by 45 m, and arranged in a randomized complete block design with three replicates.

The plots were managed using zero-tillage practices, with an exception to incorporate the GM into the soil with a V-blade cultivator or a tandem disc plow. The GM was turned down at full bloom from 1987 to 1992; thereafter, it was done at ~ 20% flowering in early- to mid-July (Zentner et al., 2006), which is the preferred termination practice (Mooleki, Gan, Lemke, Zentner, & Hamel, 2016). The plots were planted without preseeding tillage, but received a preseed burn-off using glyphosate at 0.29 to 0.44 kg a.e. ha^{-1} for weed control. Recommended cultivars for the area were planted using a commercial zero-till air hoe drill with row spacing of 22.9 cm. Wheat ('AC Eatonia' from 2003–2005, and 'Lillian' thereafter) was planted at the recommended rate of 67 kg ha^{-1} and lentil ('Indianhead Black Lentil') at 48 kg ha^{-1}. Canola cultivars Banner (2003–2009) and VT Barrier (2010 and 2011) were planted at a rate of 6.5 and 7.6 kg ha^{-1}, respectively, while canola cultivars 5440 (2012–2014) and L140P (2015) were planted at a rate of 10 kg ha^{-1}. Field pea ('Eclipse' from 2003–2010, and 'Meadow' thereafter) was planted at a rate of 225 kg ha^{-1}. Wheat and canola seed were treated with commercial pesticide formulations as described by Smith et al. (2017), and planted in late-April to early-May. Lentil and field pea were treated with commercial peat-based *Rhizobium* inoculant until 2008 and granular inoculant (TagTeam, Bayer Crop Science, Calgary, Alberta, Canada) from 2009 onward at a rate of 5.6 kg ha^{-1}, with seeding done in late-April to early-May. Nitrogen fertilizer (urea, 46–0–0) was mid-row banded at seeding to individual non-pulse plots at rates for each plot based on soil test NO_3–N levels taken the previous fall in the 0- to 60-cm soil depth, and based on the fertilizer recommendation guidelines of the soil testing laboratory at the University of Saskatchewan (Saskatchewan Soil Testing Laboratory, 1990). The total N (soil plus fertilizer) guidelines were 90 kg N ha^{-1} for wheat grown on fallow, 73 kg N ha^{-1} for wheat grown on stubble, and 101 kg N ha^{-1} for canola. An "N credit" for wheat grown after GM was applied to the soil test NO_3–N values, and was equal to 20% of the N measured in the above-ground legume biomass (Zentner et al., 2004). Wheat, canola, and field pea also received 22 kg P_2O_5 ha^{-1} at seeding in the form of monoammonium phosphate. Hence, field pea received about 5 kg N ha^{-1} yr^{-1}. On average, F-W-W, GM-W-W, F-W-W-W, ContW, and W-C-W-P received 29.4, 19.6, 34.4, 48.7, and 38.5 kg N ha^{-1}, respectively (Table 1). Canola also received sulfur at an average rate of 16.1 kg SO_4 ha^{-1}. This overall fertilization strategy is based

TABLE 1 Annual N fertilizer applied (kg N ha^{-1}) at Swift Current, Saskatchewan, Canada from 2004 to 2015

Year	Rotation[a] F-W-W	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean
2004	28	22	34	48	43	35
2005	25	17	35	54	42	35
2006	33	19	36	56	45	38
2007	23	11	25	37	27	25
2008	25	13	34	48	42	32
2009	32	13	37	40	35	32
2010	23	12	24	33	26	24
2011	38	27	42	54	36	40
2012	28	23	36	57	41	37
2013	27	25	31	48	44	35
2014	34	22	40	59	46	40
2015	37	30	40	51	37	39
Mean	29	20	34	49	39	

[a]F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea.

on crop needs and residual nutrients, and considers the effect of previous cropping or phase. This differentiates the systems from each other as each is managed individually. Our strategy differs from other studies where the crops are fertilized with a fixed fertilizer rate, irrespective of residual nutrients or previous crop, which can negatively compromise the results.

All crops, except GM, received in-crop herbicides for weed control each year as described by Smith et al. (2017). Weed control post-termination of the GM was achieved by one tillage operation with the V-blade cultivator or by herbicides. Herbicides were applied to the fallow areas from early June using tank mixes of glyphosate plus dicamba and 2,4-D amine, with three to four herbicide applications over the 21-mo fallow period to control weeds. All plots received 2,4-D ester applied in fall to control winter annual broadleaf weeds.

2.2 | Soil and plant sampling and analysis

Wheat and field pea were harvested at full maturity (mid-Aug. to early-Sept.) using a plot combine, equipped with a direct-cut header. Canola was swathed when the seeds in the bottom third of the pods were mature, then left to air-dry for approximately 10 d before threshing the grain. The stubble of all crops was cut to a height of about 30 cm to enhance snow trapping and soil moisture conservation (Zentner et al., 2006). The crop residues that moved through the combine at harvest were chopped and uniformly spread across the respective plots to help protect the soil against erosion and maintain SOM levels. The straw and grain samples were dried at 70°C to constant weight, ground with a Wiley-Thomas mill (Thomas Scientific, Swedesbro, NJ) or Perten 3303 Laboratory mill (PerkinElmer, Hägersten, Sweden) to pass a 1-mm screen, and analyzed for N concentration using the Kjeldahl method (Starr & Smith, 1978). Wheat protein was taken as percent grain N times 5.72, and adjusted to 13.5% moisture content (Smith et al., 2017; Zentner et al., 2006). Canola and field pea protein were taken as percent grain N times 6.25, then adjusted to 8% moisture for canola and 16% for field pea (Smith et al., 2017).

Composite soil samples (2 cores per plot) were collected from all plots before planting in spring, shortly after harvest (except in 2010, 2011, and 2015) and just before freeze-up in fall at the 0- to 15-, 15- to 30-, and 30- to 60-cm depths. A portion of each sample was analyzed for gravimetric soil water content by oven drying at 105°C. Another portion was air-dried, sieved at < 2 mm, and analyzed for NO_3–N. The chemistry lab where the soil samples were analyzed was not designed to handle fresh soil samples, thus the soil samples were air-dried prior to analysis. We're aware that changes in the amounts of NO_3–N may occur after air-drying of soil samples, however, this method of handling and storing soil samples in this long-term study has been consistent from the initiation of the study (Campbell et al., 2008). The NO_3–N concentrations (mg kg^{-1}) were converted to kg N ha^{-1} by assuming a bulk density of 2.24 Mg m^{-3} for each 15-cm depth segment (Saskatchewan Soil Testing Laboratory, 1990) as used previously by Campbell et al. (2008). Actual field bulk density was not used in the conversion as it was either not measured every year, in all plots, and/or at all depths.

2.3 | Apparent in-season net N mineralization

Apparent net N mineralization during the growing season was calculated separately for each phase of the rotation using the N budget approach:

$$\text{ANM} = \left(\text{Crop uptake} + \text{Harvest soil N}_{a,b}\right) - (\text{Spring soil N} + \text{Fertilizer N}) \quad (1)$$

where ANM (kg N ha^{-1}) is apparent in-season net N mineralization, crop uptake (kg N ha^{-1}) is total above-ground crop N uptake, harvest soil $N_{a,\,b}$ (0–60 cm; kg N ha^{-1}) is soil NO_3–N measured soon after crop harvest (a = crop phase) or in late fall (b = fallow phase), spring soil N (0–60 cm; kg N ha^{-1}) is soil NO_3–N measured before planting and fertilizer application, and N fertilizer (kg N ha^{-1}) is the amount of fertilizer N added. For the fallow phase, crop N uptake and fertilizer N added were set to zero. For the pulse phase, ANM includes N-fixed N during the growing season. This process assumes that N losses through leaching was minimal, although this may be possible under wet conditions (Campbell et al., 2008). In a study to determine potential N leaching to the deeper soil zones, Campbell et al. (2006) measured NO_3 to 4.5-m depth by 0.3-m increments in 10 cropping systems, and found that in this semiarid environment, NO_3 leaching was not great, with a total of 180 kg N ha^{-1} leached in 37 yr under a fallow-wheat fertilized system, and there was little evidence of leaching in continuously cropped treatments. In addition, we assumed that N loss by runoff, denitrification, and volatilization, and N gained by wet and dry depositions were negligible (Campbell et al., 2008). In these no-till soils, banding of N fertilizer below the soil surface during seeding significantly reduces NH_3 volatilization, although not completely (Rochette et al., 2009; Sheppard, Bittman, & Bruulsema, 2010). The focus here was on in-season net N mineralization, since this was the period for crop utilization of mineralized N. Although N can be mineralized in the non-growing season, we believe that this would be reflected in spring soil NO_3–N content.

2.4 | Nitrogen use efficiency

Nitrogen use efficiency was estimated as N fertilizer use efficiency (FUE) and available N use efficiency (NUE). The FUE was calculated as:

$$\text{FUE}_{\text{G,P}} = \frac{Y_{\text{G,P}}}{\text{Fertilizer N}} \quad (2)$$

where $\text{FUE}_{\text{G,P}}$ is the N fertilizer use efficiency of grain and protein production (kg^{-1} kg^{-1}), $Y_{\text{G,P}}$ is the grain and protein yield (kg ha^{-1}), respectively, and fertilizer N (kg N ha^{-1}) is the amount of fertilizer N added. The NUE was calculated by including spring NO_3–N and ANM in addition to N fertilizer applied as described below:

$$\text{NUE}_{\text{G,P}} = \frac{Y_{\text{G,P}}}{\text{Fertilizer N} + \text{Soil NO3-N} + \text{ANM}} \quad (3)$$

where $\text{NUE}_{\text{G,P}}$ is the available N use efficiency of grain and protein production (kg^{-1} kg^{-1}), $Y_{\text{G,P}}$ is the grain and protein yield (kg ha^{-1}), respectively, fertilizer N (kg N ha^{-1}) is the amount of fertilizer N added, soil NO_3–N is the soil NO_3–N (0–60 cm; kg N ha^{-1}) measured before planting, and ANM (kg N ha^{-1}) is the apparent in-season net N mineralization.

2.5 | Statistical analysis

All phases of each rotation were present every year, allowing for the analysis to be performed on a system-basis (Gan et al., 2014; Sainju, Lenssen, Allen, Stevens, & Jabro, 2017). Thus, all variables were determined for the complete rotation system where the data for phases were averaged within a rotation system and the averaged value was used for a rotation system. In the case of total grain and protein yield, the actual values of each crop were used, and averaged across the number of phases for each system. Parameters such as grain and protein yield were zero for fallow phases in the calculation. Fall NO_3–N was square root transformed, while NUE_G, FUE_G and FUE_P were log transformed to meet the assumption of normality and homogeneity of variance. Analysis of variance was performed using the PROC MIXED procedure of SAS (SAS Institute, 2013) using repeated measures with a first-order autoregressive covariance structure. Rotation, year and their interaction were regarded as fixed effects, with data collected over time (year) regarded as repeated measurements. With wheat as the most common crop, we also determined the effect of preceding phase on wheat grain and protein yields, with preceding phase, year, and their interactions as fixed effects, and data collected over time as repeated measurements. Differences were considered statistically significant at $P < .05$. Means were separated with a posthoc least square means test using the PDIFF option. The SLICE statement of SAS was used to partition the significant interactions.

Grain and protein yield stability of the rotation systems were examined by regression analysis as described by Finlay and Wilkinson (1963). In this procedure, the mean grain and protein yield of each rotation system in each year was regressed against the overall mean yield across rotation systems (site yield) in each year using the PROC REG procedure in SAS (SAS Institute, 2013). This overall mean yield in each year was regarded as a growing condition, and was ranked from ‘low-yielding’ to ‘high-yielding’ conditions. To determine whether the slope of the regression differed from a value of one, contrast using the TEST statement in the PROC REG procedure was done (Coulter et al., 2011). Subsequently, the slopes were plotted against the mean yield of each rotation system over the 12-yr study period. Linear slopes ≈ 1.0 indicate average stability. Rotation systems with average stability and high mean yield are considered to have general adaptability, while those with low mean yield are considered to be poorly adapted to the various growing conditions. Rotation systems with slopes > 1.0 are increasingly sensitive to environmental change and have below average stability, suggesting that they are well adapted to 'high-yielding' conditions. Conversely, rotation systems with slopes < 1.0 have a greater level of resistance to environmental change and have above average stability, suggesting that they are best suited to 'low-yielding' conditions.

3 | RESULTS

3.1 | Growing season conditions

At the initiation of our analysis in 2003, growing season (May–Aug.) precipitation (GSP) was 30% below the 50-yr average (1965–2015) while mean air temperature was 8% above normal (Figure 1). The 2007 and 2010 growing seasons were the driest and wettest, respectively, while the 2004 and 2006 seasons were the coolest and hottest, respectively. Overall, we considered 2004 and 2010 as cool and wet, 2003, 2006, 2007, and 2015 as warm and dry, and 2009 as cool and dry.

3.2 | Grain and protein yield

A preliminary assessment of wheat grain yield equivalent, based on wheat as the most common crop, was examined to compare among systems. The wheat-equivalent yield was calculated on a plot basis by using crop price and yield as described by Liu et al. (2019). The wheat-equivalent yield for wheat was exactly the same as the actual wheat yield (not shown). Wheat-equivalent yield for canola and field pea were, on average, higher than wheat (not shown). The results using wheat-equivalent yield to compare the systems were similar to using the annualized system yield where the actual yield of each crop was used in the calculation, except in a few minor cases. Given the similarity of the results between the annualized-system yield where the actual yield of each crop was used in the calculation, and wheat-equivalent yield, as well as the fact that grain prices, especially canola and peas, are highly unstable, we believed it was best to use the actual yield of each crop for calculating the annualized-system yield and for comparing rotation systems. Therefore, our results and subsequent discussion on total grain yield was based on actual yields and not wheat-equivalent yield. Also, we present the protein yields of different systems, as we believe it provides additional values for comparison between systems.

We found significant ($P < .001$) effects of rotation system, year and their interaction on annualized grain and protein yield (Table 2). Annualized grain yield for W-C-W-P was higher than all other systems in 3 yr with > 30% above normal GSP and 2 yr with ± 10% of normal GSP; it was also higher than other systems, except ContW in 3 yr with > 15% above normal GSP and 1 yr with 18% below normal GSP (Table 3). Overall, the W-C-W-P system produced higher grain yield than ContW in 8 of 12 yr. Annualized grain yield for ContW was higher than the other systems (except for W-C-W-P) in 4 yr with > 15% above normal GSP. Annualized protein yield was higher for W-C-W-P than all other systems in all years except in 2012 (15% above normal GSP), when it was similar to ContW (Table 3). The ContW system produced more protein than the two fallow systems in 4 yr with > 15% above normal GSP, 1 yr with near normal GSP, and similar protein yields in 4 yr with either near normal or below normal GSP.

Annualized grain and protein yield increased as fallow frequency decreased. The F-W-W, F-W-W-W and GM-W-W had similar grain yield in seven of the 12 yr. The GM-W-W had lower grain yield than the fallow systems in the hot and dry years of 2006 and 2007, in 2009 with 18% below normal GSP when GM-W-W was lower yielding than F-W-W-W, and in 2010 (91% above normal GSP) and 2013 (near normal GSP) when grain yields were higher for GM-W-W than F-W-W. The GM-W-W system had the lowest protein yield in 2007, the driest and hottest year, while in the similarly dry and hot year of 2006, it was lowest but not significantly different from F-W-W. In contrast, the GM-W-W system produced 14 to 18% and 20 to 24% higher protein than the fallow systems in 2 yr with about 30% above normal GSP (2004 and 2011), and 25 to 34% higher than F-W-W in 4 yr with near or > 15% above normal GSP (2008, 2010, 2012, and 2013). Overall, annualized grain yield was more affected by year than by rotation system. Conversely, annualized protein yield was influenced more by rotation system than by year. On average across the 12-yr period, grain and protein yields were 14 to 38% and 33 to 66% higher, respectively, for W-C-W-P than the other systems. Annualized grain yield followed the order of W-C-W-P > ContW > F-W-W-W > GM-W-W = F-W-W, while the order for protein yield was W-C-W-P > ContW > GM-W-W = F-W-W-W > F-W-W (Table 3).

Wheat grain yield was higher after fallow (F-[W]-W and F-[W]-W-W), followed by GM (GM-[W]-W) and in the diversified system ([W]-C-W-P and W-C-[W]-P), and lower for F-W-W-(W) and ContW (Figure 2). Wheat protein yield followed a quite similar trend, as it was higher after fallow and GM, and lower after wheat stubble in the fallow and ContW systems (Figure 2).

3.3 | Stability

The GM-W-W system had below-average grain and protein yields in low-yielding conditions, and near-average protein yield in high-yielding conditions (Figure 3a, 3b). The slope of the linear regression for GM-W-W was similar ($P > .05$; Table 4 and Figure 3c, 3d) to 1 for grain (1.06) and protein yield (1.22). Annualized grain and protein yields were lowest

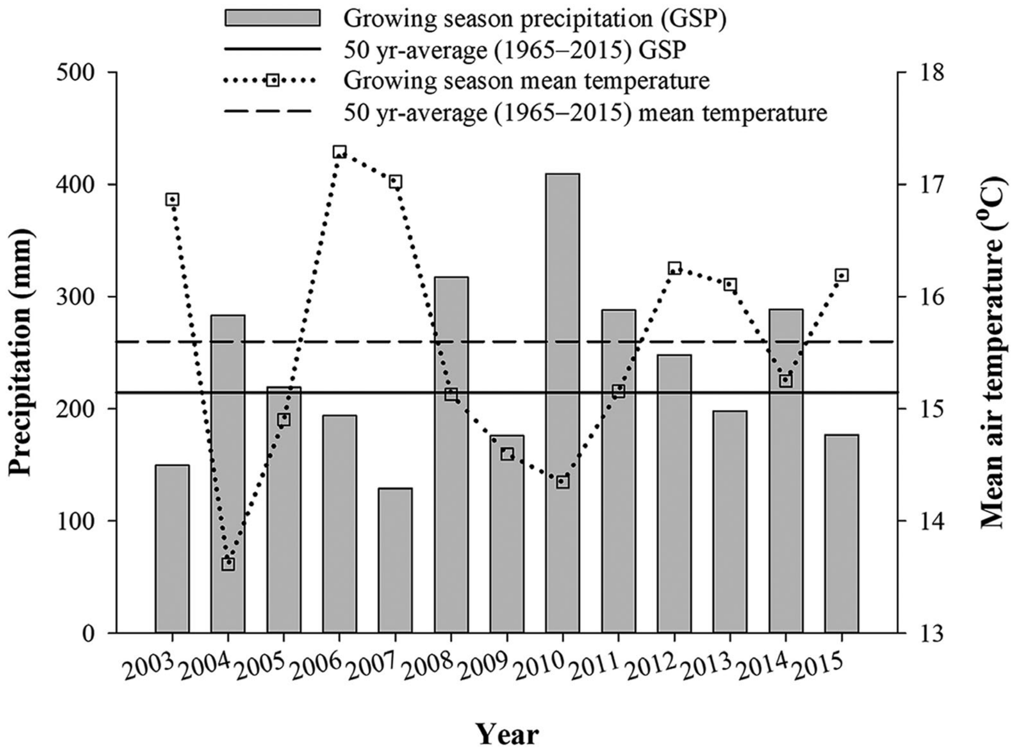

FIGURE 1 Growing season precipitation and measn air temperature (May–Aug.) during the study period at Swift Current, Saskatchewan, Canada from 2003 to 2015. This data was obtained from a weather station at the experimental site

TABLE 2 Analysis of variance on the interactive effect of rotation system and year on annualized grain and protein yield, N fertilizer applied, spring NO_3–N and fall NO_3–N in the 0–60 cm soil depth, apparent in-season net N mineralization (ANM), N fertilizer use efficiency (FUE_G; FUE_P) and available N use efficiency (NUE_G; NUE_P) in relation to grain and protein yield at Swift Current, Saskatchewan, Canada from 2004–2015

Model	Grain yield	Protein yield	Spring NO_3–N	Fall NO_3–N	ANM	FUE_G	FUE_P	NUE_G	NUE_P
	F value								
Rotation (R)	116.2***	154.3***	68.2***	34.3***	30.7***	94.7***	120.5***	76.9***	204.2***
Year (Y)	141.4***	51.3***	15.8***	20.0***	19.7***	32.4***	25.6***	132.9***	60.9***
R × Y	4.1***	3.6***	2.6***	2.3***	6.3***	2.8***	2.9***	4.9***	9.2***

***Significant at the $P < .001$ level.

in the GM-W-W system in dry and hot years, and when the previous year was also hot and dry.

The fallow systems had mostly below-average grain and protein yields, with a few exceptions (Figure 3a, 3b), and their slopes (< 0.8) were significantly ($P < .05$) less than 1 (Table 4; Figure 3c, 3d). More specifically, the fallow systems generally produced above- or near-average grain and protein yields only in very low-yielding conditions (Figure 3a, 3b). Interestingly, the gap between the fallow systems and the average site yield increased as grain and protein yield progressed from low to high-yielding conditions.

The ContW system produced near or above-average grain yields, which increased from low-yielding to high-yielding conditions (Figure 3a), and had a slope > 1 ($P < .05$; Table 4 and Figure 3b). For protein yield, however, the ContW system produced average or above-average yield across all conditions (Figure 3b), with a slope close to 1 ($P > .05$; Table 4 and Figure 3d). The W-C-W-P system had low yield stability with slopes significantly > 1 ($P < .05$; Table 4 and Figure 3c, 3d), and consistently had above-average grain and protein yields across all conditions.

3.4 | Nitrogen dynamics

There were significant ($P < .001$) effects of rotation system, year, and their interaction on spring and fall soil NO_3–N content, and ANM (Table 2). The GM-W-W system had higher spring and fall NO_3–N content than the other systems (Table 5). More specifically, spring NO_3–N content was higher under GM-W-W than under the other rotations in eight of 12 yr (Table 5). The W-C-W-P, and more so the ContW

TABLE 3 Annualized grain and protein yields in five long-term crop rotations at Swift Current, Saskatchewan, Canada from 2004 to 2015

Year	F-W-W[a]	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean
	Grain yield (kg ha^{-1})					
2004	2297b[b]	2522b	2485b	3074a	3204a	2716A
2005	1586c	1543c	1732bc	1848b	2363a	1814DE
2006	1506a	1150b	1539a	1563a	1659a	1483G
2007	1406a	896b	1348a	1323a	1491a	1293H
2008	1448c	1655bc	1635bc	1859ab	1986a	1716EF
2009	1529ab	1295b	1566a	1545a	1666a	1520G
2010	1333d	1729c	1558cd	2010b	2410a	1808DE
2011	2123c	2311c	2213c	2801b	3049a	2499B
2012	1400b	1566b	1517b	1816a	1927a	1645F
2013	2001d	2264bc	2069cd	2434b	3069a	2368C
2014	1710b	1597b	1725b	1790b	2448a	1854D
2015	1230c	1351bc	1354bc	1536ab	1659a	1426G
Mean	1631d	1656d	1728c	1967b	2244a	
	Protein yield (kg ha^{-1})					
2004	304c	358b	314c	394b	500a	374A
2005	203b	219b	222b	228b	396a	254EF
2006	232bc	197c	238b	258b	327a	250EFG
2007	251b	168c	242b	249b	318a	246FG
2008	217c	278b	252bc	288b	380a	283CD
2009	216b	194b	227b	229b	296a	233GH
2010	184d	247bc	215cd	274b	405a	265DE
2011	268c	332b	277c	348b	441a	333B
2012	171d	223bc	195cd	255ab	270a	223H
2013	232d	289bc	251cd	308b	418a	300C
2014	204c	215bc	215bc	251b	395a	256DF
2015	203c	221bc	224bc	260b	322a	246FG
Mean	224d	245c	239c	279b	372a	

[a]F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea.

[b]Values followed by the same lowercase letters within rows and uppercase letters within columns are not significantly different ($P > .05$).

system, generally had the lowest spring NO_3–N content in most years. Overall, spring NO_3–N content followed the order of GM-W-W > F-W-W > F-W-W-W = W-C-W-P > ContW. Similarly, fall NO_3–N content was highest under GM-W-W in three of 12 yr (Table 5), highest under GM-W-W, except for F-W-W in 2004, ContW in 2015, F-W-W and W-C-W-P in 2006, F-W-W and ContW in 2007, and F-W-W and F-W-W-W in 2012. On average, fall NO_3–N content was highest in 2009, 2015, 2006, and 2007, and lowest in 2013, and followed the order of GM-W-W > F-W-W = F-W-W-W > W-C-W-P = ContW.

The ANM was higher for GM-W-W and W-C-W-P than the other systems in 2004 and 2008 (Table 5). ANM was highest for GM-W-W in 2005 and 2013. The W-C-W-P had higher ANM than the other systems in 2014, and higher than ContW in 2005, 2006, 2007, and 2012. The ANM was lowest for ContW in 2006, 2008, and 2012. There was some possible N immobilization occurring under ContW in most years except 2004, 2007, and 2009. Possible immobilization may have also occurred under W-C-W-P in 2005, and under F-W-W in 2006, 2013, and 2014.

3.5 | Nitrogen use efficiency

Rotation system, year, and their interaction significantly ($P < .001$) influenced FUE and NUE for grain and protein yield (Table 2). The GM-W-W system had a higher FUE_G than other systems in five of 12 yr; it was also higher in 2004 except for F-W-W and W-C-W-P, and in 2011 and 2015 except

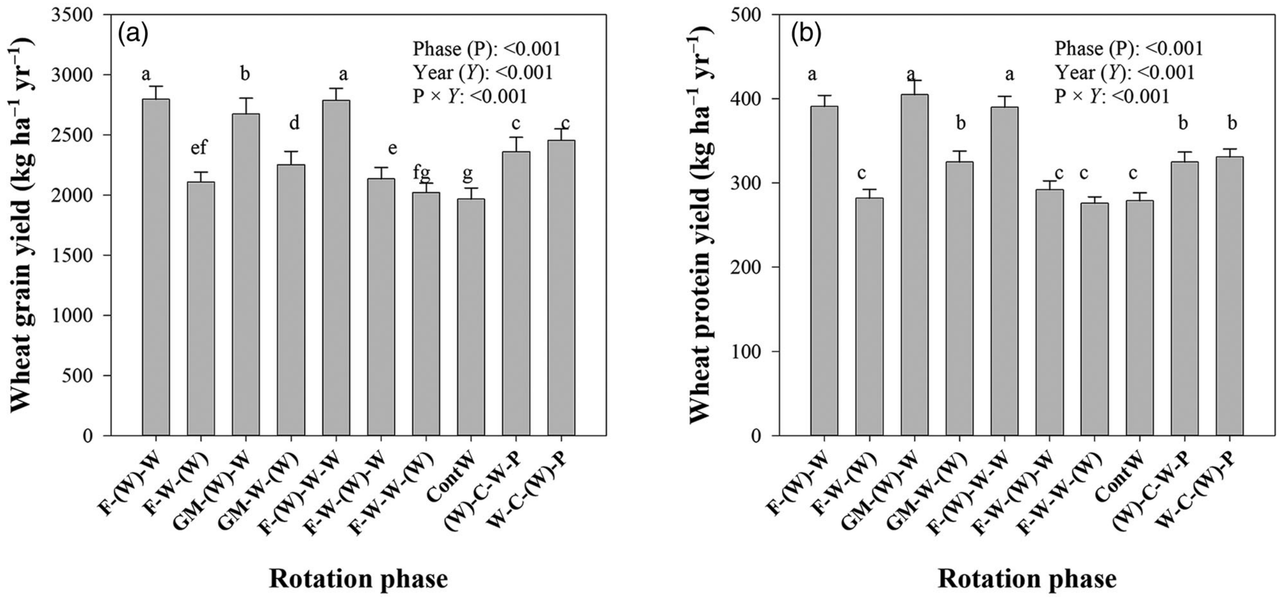

FIGURE 2 Wheat grain (a) and protein (b) yield following different rotation phases at Swift Current, Saskatchewan, Canada from 2004 to 2015. F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea. Letters in parenthesis represent the rotation phase. Bars with the same lowercase letters are not significantly different ($P < .05$)

for W-C-W-P (Table 6). Similarly, GM-W-W had the highest FUE_P in five of 12 yr (2005, 2008, 2009, 2010, and 2012), and higher than other systems except W-C-W-P and F-W-W in 2004 and 2007, and W-C-W-P in 2011, 2014, and 2015. The FUE_G for ContW was the lowest in 2005, 2006, 2007, 2012, 2013, and 2014, while FUE_P for ContW was lowest in four of 12 yr (2005, 2006, 2007, and 2008), and lower than all systems except F-W-W and/or F-W-W-W in other years.

The W-C-W-P had similar FUE_G as GM-W-W in six of 12 yr (2004, 2006, 2007, 2011, 2013, and 2015). The fallow systems had similar FUE_G in all years except 2005, when it was higher in F-W-W than in F-W-W-W. The ContW had the lowest FUE_P in four of 12 yr (2005, 2006, 2007, and 2008), while in other years, it was lower than all systems except F-W-W and/or F-W-W-W. The FUE_P for W-C-W-P was similar to GM-W-W in seven of 12 yr. On average, FUE_G followed the order of GM-W-W > W-C-W-P = F-W-W > F-W-W-W > ContW, while FUE_P followed GM-W-W > W-C-W-P > F-W-W > F-W-W-W > ContW (Table 6).

When all available N sources, excluding atmospheric deposition, were included, NUE displayed the opposite pattern as FUE. The NUE_G and NUE_P were lowest for GM-W-W in all years, except for NUE_G in 2008 where it was similar to W-C-W-P, and in 2012 where it was similar to the fallow systems (Table 6). Similarly, NUE_P was lowest for GM-W-W except in 2006 and 2012 where it was similar to F-W-W-W, and in 2014 where it was similar to F-W-W (Table 6).

Compared to other systems, NUE_G was highest for ContW in 2004 and 2008, for W-C-W-P in 2005, and for ContW and W-C-W-P in 2012 (Table 6). The W-C-W-P system had a higher NUE_P than other systems in four of the 9 yr this was estimated (2005, 2006, 2008, and 2009). In the other 5 yr, W-C-W-P had high but similar NUE_P as ContW. In all cases, NUE values for the fallow systems were intermediate.

4 | DISCUSSION

4.1 | Productivity of rotation systems

As mentioned previously, annualized grain yield using actual grain yields of each crop and not wheat-equivalent yields were presented and discussed. A similar approach using actual yield was used in other studies to compare the productivity of different cropping systems (Gan et al., 2015; Sainju et al., 2017).

The higher annualized grain and protein yields of the W-C-W-P and ContW systems compared to the other systems were expected since the W-C-W-P and ContW systems were continuously cropped, while the fallow and the GM systems had one out of 3 to 4 yr with no crop being grown. Annualized grain yield of the systems in the current study were similar to those reported for the 2004 to 2014 period by Smith et al. (2017); however, it was 8 and 6% higher for F-W-W and F-W-W-W, respectively, than that reported by Zentner et al. (2003) for the first 12 yr of the experiment, partly due to differences in the wheat cultivars grown. The GSP during the first and last 12-yr periods (243 mm vs. 244 mm) were similar, while

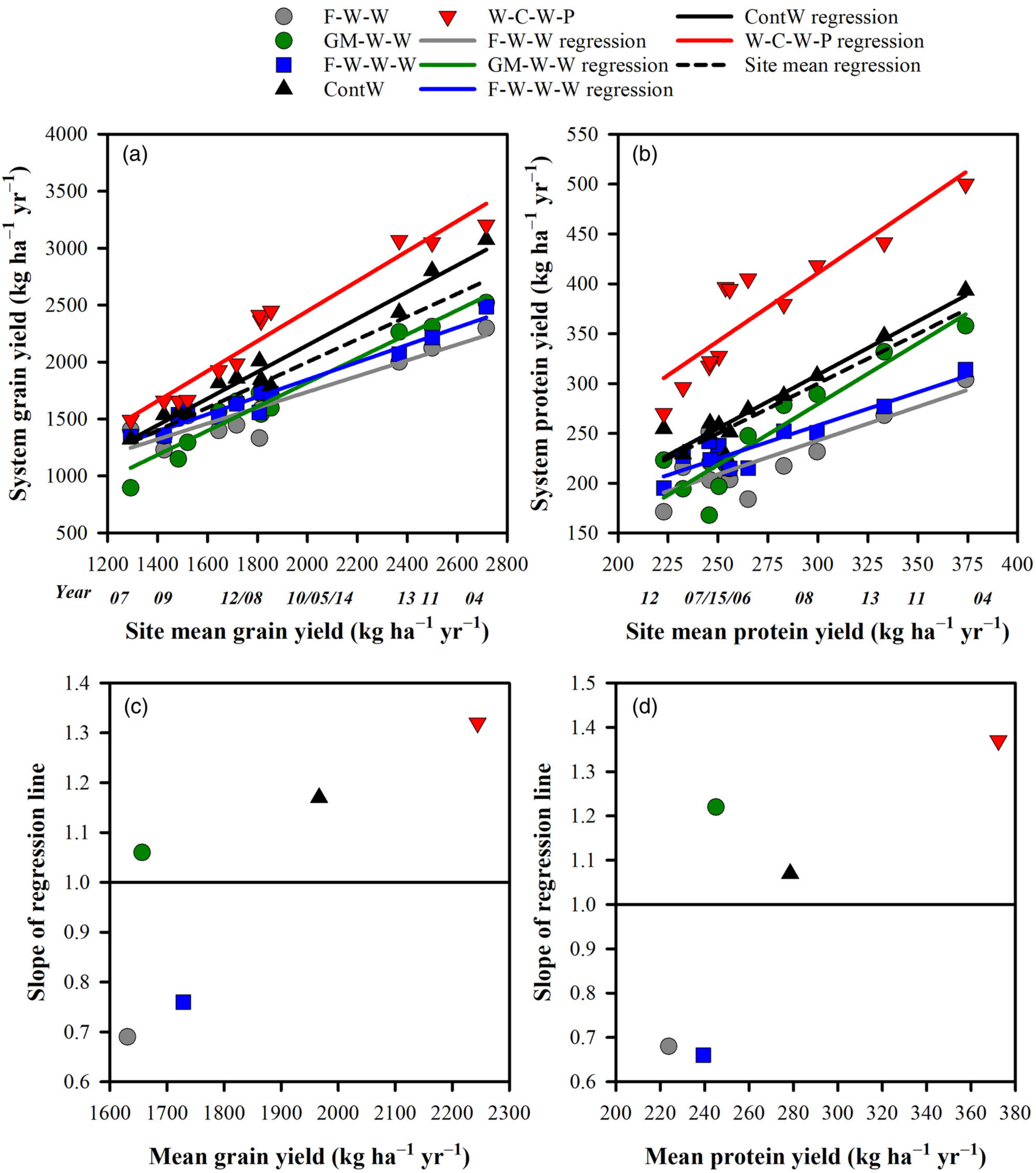

FIGURE 3 Stability of five long-term cropping systems at Swift Current, Saskatchewan, Canada over a 12-yr period (2004–2015). Relationship between cropping system mean yield (a) and site mean yields (b), and relationship between regression coefficient and cropping system mean yield (c, d). F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea

potential evapotranspiration (PET), estimated at 70% of Class A pan evaporation for cropped systems (Martin, Gilley, & Skaggs, 1991), was only 5% higher in the first (669 mm) than in the last 12 yr (633 mm; data not shown). The higher annualized grain yield of the W-C-W-P than ContW was partly due to the fact that wheat yields in the W-C-W-P system averaged 20 to 25% higher than that of ContW (Figure 2); this more than compensated for the lower canola and field pea grain yields (data not shown). The increase in annualized grain and protein yield as fallow frequency

TABLE 4 Regression results relating mean grain and protein yields of each rotation against overall mean yield across rotation systems in five long-term crop rotations at Swift Current, Saskatchewan, Canada from 2004 to 2015

	Parameter estimates				
	kg kg^{-1}				
Rotation[a]	Intercept	Slope	r^{2} [b]	Model significance	Test of slope = 1
		Grain yield			
F-W-W	351.7	0.69	.86	<.001	<0.001
GM-W-W	−296.7	1.06	.95	<.001	0.453
F-W-W-W	323.0	0.76	.96	<.001	0.003
ContW	−193.6	1.17	.97	<.001	0.032
W-C-W-P	−184.4	1.32	.95	<.001	<0.001
		Protein yield			
F-W-W	39.8	0.68	.66	.001	0.032
GM-W-W	−85.7	1.22	.86	<.001	0.145
F-W-W-W	58.7	0.66	.85	<.001	0.026
ContW	−13.6	1.07	.92	<.001	0.613
W-C-W-P	0.86	1.37	.81	<.001	0.016

[a]F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea.
[b]r^2, coefficient of determination.

decreased was in agreement with previous studies (Gan et al., 2015; Rosenzweig, Stromberger, & Schipanski, 2018; Smith et al., 2017), and was mostly related to the absence of a crop during the summer fallow and GM phases. Differences in protein yield among rotation system is a partial reflection of the specific crops within the rotations. The inclusion of field pea in the W-C-W-P rotation increased overall protein yield compared to the other systems. Pulse crops, such as field pea, have a much higher seed N concentration, and often produce equivalent or greater seed yield than cereals and oilseeds, as observed in this study (data not shown). In addition, wheat following field pea in the W-C-W-P system had 15 to 18% higher protein yield than wheat grown on stubble in the fallow and ContW systems (Table 3). The inclusion of pulses in cropping systems can help to improve soil and human health by providing adequate protein for human consumption (Lal, 2017). Canola in the W-C-W-P system had similar protein yield to wheat grown on stubble in the fallow and ContW systems (data not shown), further contributing to the higher annualized protein yield for W-C-W-P. Although canola is primarily grown for its oil content and there's a direct inverse relationship between oil and protein content (Hossain, Johnson, Wang, Blackshaw, & Gan, 2019), meal from canola oil extraction can be used to produce protein-rich human and animal food (Hossain et al., 2019; Wanasundara, McIntosh, Perera, Withana-Gamage, & Mitra, 2016).

The variability in annualized grain and protein yield across years was not surprising, given that the study area is a moisture-limiting environment. Several studies have highlighted the critical importance of precipitation and soil moisture in this and other semiarid regions (Campbell et al., 2007b; De Jong et al., 2008; Franco et al., 2018, Kirkegaard & Hunt, 2010; Kröbel et al., 2012). Moreover, studies have indicated that crop yield in this region is affected more by precipitation during the growing season than preplant residual soil water (De Jong et al., 2008; Gan et al., 2015). We do not have sufficient soil water or other data to fully explain the higher wheat grain yield after fallow than after GM and stubble. The higher yield of the second-year wheat after GM compared to the second- and third-year wheat after fallow was likely linked to residual N from the GM, N conserved by the first year wheat stubble, as well as possible non-N benefits provided by the GM (Angus et al., 2015; St. Luce et al., 2015, 2016a).

4.2 | Stability of rotation systems

Our results indicate that the GM-W-W system was poorly adapted across the different growing conditions, as it was highly affected by changes in growing season conditions (Nielsen & Vigil, 2005; Zentner et al., 2004). Possible reasons for the poor adaptability of the GM-W-W system include lower water use efficiency (Kröbel et al., 2014; Lyon & Hergert, 2014; Zentner, Campbell, Biederbeck, & Selles, 1996). Kröbel et al. (2014) found lower water- and precipitation-use efficiency for the GM-W-W than ContW, F-W-W-W, and F-W-W, which was attributed to the negative effect of the GM on subsequent wheat yield due to lower water availability. We found lower wheat grain yield following GM than fallow (Figure 2). However, Mooleki et al.

TABLE 5 Average annual spring and fall NO_3–N content, and apparent in-season net N mineralization at Swift Current, Saskatchewan, Canada from 2004 to 2015

Year	F-W-W[a]	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean
	Spring NO_3–N content					
	kg N ha^{-1}					
2004	45.5a[b]	43.7a	41.0a	30.5b	27.1b	36.6ABC
2005	40.5b	51.8a	34.6bc	27.7c	28.8c	36.7BC
2006	40.8b	64.3a	33.3bc	30.8c	31.8bc	40.2ABC
2007	37.4b	56.6a	35.2b	35.4b	38.3b	40.6AB
2008	38.0b	48.1a	33.1b	32.1b	30.0b	36.3C
2009	35.2bc	64.2a	36.7bc	28.6c	41.2b	41.2A
2010	32.3 cd	56.8a	36.9bc	22.5d	43.6b	38.4ABC
2011	24.7ab	33.6a	16.7b	19.4b	23.4b	23.5E
2012	27.3b	44.0a	24.5b	27.7b	22.5b	29.2D
2013	36.9a	32.9a	31.7ab	14.6c	22.8bc	27.8DE
2014	31.0a	38.2a	20.7b	13.2b	17.9b	24.2E
2015	22.8b	52.0a	26.7b	21.8b	30.1b	30.7D
Mean	34.4b	48.8a	30.9c	25.4d	29.8c	
	Fall NO_3–N content					
	kg N ha^{-1}					
2004	35.0ab	45.3a	26.9b	16.8c	16.3c	28.0BC
2005	25.5b	41.0a	25.8b	16.2b	18.2b	25.4CDE
2006	39.4ab	53.3a	32.7b	31.6b	44.8ab	40.3A
2007	41.9ab	52.7a	35.5bc	37.5abc	28.4c	39.2A
2008	26.4b	48.7a	24.9b	31.0b	27.7b	31.7B
2009	38.1a	55.9a	41.3a	40.1a	46.7a	44.4A
2010	19.8a	28.7a	19.2a	17.0a	21.6a	21.3EF
2011	20.4bc	22.1bc	37.0a	10.9c	25.1b	23.1DEF
2012	30.1ab	35.5a	32.9ab	23.8bc	15.1c	27.5BCD
2013	21.1b	44.7a	20.0b	11.3c	9.6c	21.3F
2014	20.6a	29.7a	21.6a	17.8a	23.7a	22.7CDEF
2015	38.8bc	57.4a	36.5bc	44.8ab	29.9c	41.5A
Mean	29.8b	42.9a	29.5b	24.9c	25.6c	
	ANM[c]					
	kg N ha^{-1}					
2004	15.4b	50.4a	13.7b	3.8b	40.4a	24.7A
2005	0.48b	18.8a	1.4b	−13.7c	−0.59b	1.3D
2006	−1.2ab	−1.2ab	8.2a	−8.5b	10.9a	1.6D
2007	33.9a	14.0bc	24.2ab	3.0c	21.2ab	19.3AB
2008	8.0b	44.0a	11.5b	−8.3c	42.8a	19.6AB
2009	19.3a	29.9a	10.0a	17.9a	14.7a	18.4B
2010	–	–	–	–	–	
2011	–	–	–	–	–	
2012	12.6a	10.8a	9.6a	−19.6b	4.1a	3.5D
2013	−0.33c	38.8a	2.6c	−0.08c	19.3b	12.1C

(Continued)

TABLE 5 Continued

Year	F-W-W[a]	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean
	Spring NO_3–N content					
	kg N ha^{-1}					
2014	−3.3b	9.0b	0.39b	−2.6b	30.3a	6.8D
2015	–	–	–	–	–	
Mean	**9.4b**	**23.8a**	**9.1b**	**−3.1c**	**20.3a**	

[a]F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea.

[b]Values followed by the same lowercase letters within rows and uppercase letters within columns are not significantly different ($P > .05$).

[c]Harvest soil NO_3–N data were not collected in 2010, 2011, and 2015, hence ANM for these years could not be estimated.

(2016) found that GM did not reduce soil water relative to summer fallow. It must be noted that precipitation during the growing season may have a more dominant role in affecting crop yield compared to water availability in early spring (De Jong et al., 2008; Gan et al., 2015). Our findings could also be linked to the relatively low biomass produced by the GM crop (Zentner et al., 1996), resulting in little biomass cover to trap snow and conserve soil moisture in the subsequent growing season by reducing evapotranspiration. One may assume that the shallow tillage used to turn down the GM probably enhanced soil moisture loss (Tanaka & Aase, 1987), however, the tillage effect may be confounded with the water use of the GM. Mooleki et al. (2016) showed that the method of GM termination (glyphosate vs. incorporation) had no effect on soil moisture and available N at termination or the following spring. Additionally, low GSP in some years likely reduced N mineralization from the GM, thereby minimizing the effect of the N credit attributed to the GM. Nonetheless, further investigation is required to better understand these findings.

The higher protein yield in favorable years for the GM-W-W system in comparison to the fallow systems reflects an enhancement in the soil N supply capacity (Mooleki et al., 2016; St. Luce et al., 2015, 2016a) and increased available soil moisture in those years (Zentner et al., 2004; 2006; O'Donovan et al., 2014). Wheat grown after GM had similar protein yield with wheat grown after fallow, but had lower grain yield than wheat grown after fallow. Moreover, only in 2011 did wheat grown after GM have higher protein yield than wheat after any other phase, while the wheat grain yield after GM was not the highest in any year (data not shown). The GSP was highest in 2010, with 2011 having higher spring soil water than all other years except 2014 (data not shown). Our results suggest that inclusion of GM in a conventional cropping system in semiarid environments may only be beneficial when sufficient moisture is conserved during the GM phase, is available to enhance N mineralization from the GM, and is available to improve yield in the subsequent crop phase (Lyon & Hergert, 2014; Zentner et al., 2006).

Although soil moisture loss through evaporation can be significant during summer fallow due to the bare soil conditions (De Jong et al., 2008; Mooleki et al., 2016; Tanaka & Aase, 1987), allowing land to remain in fallow for a growing season can conserve soil moisture, albeit an average of about 20% more than continuous cropping (Gan et al., 2015), and can also enhance soil N availability (Campbell et al., 2008; Gan et al., 2015). These fallow effects are sufficient to boost yields in the subsequent growing season and were in agreement with our findings, as wheat grain yield was highest after fallow and lowest after stubble, especially in the ContW and the last phase of the F-W-W-W system. Our results suggest that the fallow systems had above-average stability, and therefore they were less affected by growing conditions. This exemplifies why fallowing played an important role in traditional subsistence farming systems. However, fallow systems are unable to take advantage of high-yielding conditions for grain and particularly protein yield, making them undesirable in comparison to continuous cropping systems in contemporary agricultural production. However, the fallow systems may still be a suitable option for low-yielding conditions, with greatest benefit in conditions with low moisture availability, and hot and dry conditions.

The ContW system could be considered as having below-average stability and better suited to normal- to high-yielding conditions for grain production, but with general adaptability across growing conditions for protein production. Therefore, grain yield, and to a lesser extent protein yield, for the ContW system can be expected to increase under favorable growing conditions. A low tendency for improvements in protein yield for ContW could be expected because of a dilution effect caused by the increase in grain yield under favorable conditions (Zentner et al., 2006). In contrast, the W-C-W-P system was very responsive to changes in growing conditions, and has below-average stability. The W-C-W-P system performed best under favorable conditions, and also performed well under less favorable conditions, making it a desirable cropping option with respect to its robustness and reliability. In this regard, relative to W-C-W-P, the yield stability of the fallow- and GM-containing systems is perhaps more appropriately viewed as a yield inefficiency, in which the systems are less able to utilize available resources to produce

TABLE 6 Nitrogen fertilizer use efficiency (FUE_G and FUE_P), and available N use efficiency (NUE_G and NUE_P) as a function of grain and protein production in five long-term crop rotations at Swift Current, Saskatchewan, Canada from 2004 to 2015

Year	F-W-W[a]	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean	F-W-W	GM-W-W	F-W-W-W	ContW	W-C-W-P	Mean
	FUE_G						FUE_P					
	kg kg^{-1}											
2004	82.3ab	96.1a	72.4bc	64.0c	75.3abc	78.0A[b]	10.9ab	13.3a	9.1bc	8.2c	11.8a	10.6A
2005	66.7b	90.4a	50.2c	34.4d	56.1bc	59.6C	8.5b	12.8a	6.4c	4.2d	9.4b	8.3C
2006	45.9a	52.2a	42.7a	28.2b	37.4a	41.3E	7.0a	8.9a	6.6a	4.7b	7.4a	6.9D
2007	63.7a	70.6a	54.9a	36.2b	58.8a	56.8C	11.3ab	13.2a	9.8b	6.8c	12.5ab	10.7A
2008	59.7b	99.0a	48.9bc	38.2c	48.1bc	58.8C	9.0b	16.7a	7.5b	5.6c	9.2b	9.6B
2009	47.6b	97.8a	43.4b	39.3b	47.7b	55.2CD	6.7bc	14.7a	6.3c	5.8c	8.5b	8.4C
2010	59.4bc	198.2a	67.1b	48.4c	76.1b	89.8A	8.3 cd	28.9a	9.3c	6.7d	12.5b	13.2A
2011	55.7b	86.8a	52.2b	52.0b	85.6a	66.5B	7.0b	12.4a	6.5b	6.5b	12.4a	9.0BC
2012	50.9b	68.8a	42.0b	32.2c	48.0b	48.4D	6.2b	9.8a	5.4bc	4.5c	6.7b	6.5D
2013	75.8a	79.4a	68.0a	52.7b	71.1a	69.4B	8.8a	10.3a	8.2ab	6.7b	9.7a	8.7BC
2014	52.9b	72.6a	43.8b	30.4c	53.6b	50.7D	6.3b	9.8a	5.4bc	4.3c	8.6a	6.9D
2015	33.9b	45.3a	34.2b	30.2b	45.2a	37.8E	5.6b	7.4a	5.6b	5.1b	8.8a	6.5D
Mean	**57.9b**	**88.1a**	**51.6c**	**40.5d**	**58.6b**		**8.0c**	**13.2a**	**7.2d**	**5.8e**	**9.8b**	
	NUE_G						NUE_P					
	kg kg^{-1}											
2004	25.9b	21.7c	27.9b	33.6a	29.1b	27.6B	3.4b	3.1c	3.5b	4.3a	4.5a	3.8B
2005	24.2c	17.6d	24.3c	27.9b	33.6a	25.5C	3.1b	2.5c	3.1b	3.4b	5.6a	3.5C
2006	21.0a	16.6b	19.8a	20.0a	19.1a	19.3E	3.2b	2.8c	3.1bc	3.3b	3.8a	3.2D
2007	15.0b	10.9c	16.0ab	18.2a	17.3a	15.5G	2.7b	2.0c	2.9b	3.4a	3.7a	2.9E
2008	20.5a	15.8c	20.9b	24.4a	17.3c	19.8E	3.1b	2.7c	3.2b	3.8a	3.3b	3.2D
2009	17.7a	13.3b	18.8a	18.7a	18.3a	17.4F	2.5b	2.0c	2.7b	2.8b	3.3a	2.7F
2010	–	–	–	–	–	–	–	–	–	–	–	–
2011	–	–	–	–	–	–	–	–	–	–	–	–
2012	20.7b	20.4b	21.6b	27.9a	28.7a	23.8D	2.5c	2.9b	2.8bc	3.9a	4.0a	3.2D
2013	31.9bc	23.4d	31.8bc	39.0a	35.8ab	32.4A	3.7b	3.0c	3.9b	4.9a	4.9a	4.1A
2014	28.0a	23.1b	28.4a	28.3a	26.0a	26.7B	3.3bc	3.1c	3.5b	4.0a	4.2a	3.6BC
2015	–	–	–	–	–	–	–	–	–	–	–	
Mean	**22.8c**	**18.1d**	**23.3c**	**26.4a**	**25.0b**		**3.1d**	**2.7e**	**3.2c**	**3.8b**	**4.1a**	

[a]F-W-W, fallow-wheat-wheat; GM-W-W, lentil green manure-wheat-wheat; F-W-W-W, fallow-wheat-wheat-wheat; ContW, continuous wheat; W-C-W-P, wheat-canola-wheat-pea.

[b]Values followed by the same lowercase letters within rows and uppercase letters within columns are not significantly different ($P > .05$).

[c]Harvest soil NO_3–N data were not collected in 2010, 2011, and 2015, thus ANM for these years could not be estimated.

yield, with the relative yield inefficiency becoming more pronounced as growing conditions become more favorable.

Traditionally, summer fallow was viewed as a viable option for producers in this region, due in part to lower financial risk and higher yield stability compared to diversified, monoculture or intensive cropping systems (Archer et al., 2018; DeVuyst & Halvorson, 2004; Zentner & Campbell, 1988; Zentner et al., 2002). However, Smith et al. (2017) recently concluded that under current economic conditions and with participation in a crop insurance program, farm profitability can be increased with the adoption of diversified and more intensive crop rotations compared to fallow systems. In a 12-yr study conducted in North Dakota, Archer et al. (2018) concluded that more diverse crop rotations can maintain or increase crop productivity and enhance economic viability. Summer fallow will only make sense economically if it mitigates resource limitations more than it reduces overall system production. Moreover, the need to meet the demands of a rapidly growing world population, together with future technological developments, such as the genetic enhancements of cultivars for improved heat and drought tolerance, coupled with improved farming practices, will favor the use of continuous cropping over fallow systems, and extended and diversified over monoculture systems. Our study showed that W-C-W-P was more productive and consistently produced higher grain and protein yields than the other cropping systems across the wide range of growing conditions. With the advent of climate change affecting both abiotic and biotic factors, Lin (2011) argued that diversified systems are better suited to perform under changing conditions. Most previous studies focused on determining the performance of different rotation systems or specific crops within the rotation that include different frequencies of summer fallow in the treatment structure. The present study adds more value to reveal the stability and vulnerability of these rotation systems across diverse growing conditions (over years).

4.3 | Nitrogen dynamics and use efficiency of rotation systems

The higher fall NO_3–N content and N credit applied as a result of the GM can account for the lower N fertilizer applied in this system, particularly in comparison to F-W-W. The GM provides available N to subsequent crops through biological N fixation and decomposition of their N-rich above- and below-ground residues. These residues are known to have high N concentrations and low C/N ratios, which stimulates N mineralization and increases soil available N content (St. Luce, Whalen, Ziadi, Zebarth, & Chantigny, 2014, 2016a). However, it is well known that the influence of N on cropping system productivity in this semiarid region is predominantly dependent on soil moisture (Campbell et al., 2007b; Gan et al., 2015; Kröbel et al., 2012), and this was clearly evident in the GM-W-W system where increased soil N availability did not always translate to increased yields in years with lower moisture. In contrast, wheat straw has a very high C/N ratio, which can result in immobilization of added N and lower rates of N mineralization (Cao et al., 2018; Cheng, Cai, Chang, Wang, & Zhang, 2012; Qiu et al., 2012; St. Luce et al., 2014). However, a portion of the immobilized N could be re-mineralized and thus become available for subsequent wheat uptake.

Unlike the GM-W-W system, the increased N availability after fallow is often described as soil N mining, since no N is actually added to the system from external sources through biological N fixation or mineralization of crop residues. The conservation of soil moisture during the summer fallow period stimulates N mineralization (Campbell et al., 2008), resulting in lower N fertilizer application rates immediately after summer fallow. However, N fertilizer applied to wheat grown on wheat stubble in the fallow systems was higher than for ContW (data not shown). This indicates that the fallow N mineralization advantage was short-lived, compared to GM-W-W, where the two wheat phases received less N fertilizer than the corresponding wheat phases in the fallow systems. The higher N fertilizer applied in the ContW system could be due to much lower fall NO_3–N content and more instances of possible immobilization occurring (negative ANM) than other systems, although the total N guidelines for wheat on stubble (73 kg N ha^{-1}) was lower than for wheat after fallow (90 kg N ha^{-1}). The pulse crop in the W-C-W-P system received only small quantities of N fertilizer on some occasions (< 5 kg N ha^{-1}) through monoammonium phosphate application, while canola received the highest quantities of N fertilizer among all the crops in this study. As such, the lower total N fertilizer applied to W-C-W-P than ContW was due largely to the low- or no-N applied to the pulse crop. Over the 12-yr period, fall soil NO_3–N content was similar for W-C-W-P and ContW.

Previous work in the semiarid Canadian Prairie showed that crop rotation has marked effects on SOM as measured by organic N and C (Campbell et al., 2007a; Maillard et al., 2018). Those systems that increase SOM thereby immobilize N that can decrease apparent N availability to the crop (McConkey, Curtin, Campbell, Brandt, & Selles, 2002). Conversely, cropping systems that decrease SOM release N and thereby increase apparent N availability to the crop, albeit unsustainably (Fan, McConkey, Janzen, & Miller, 2018). Campbell et al. (2007a) reported that in 2003, organic N concentration followed the order of ContW > GM-W-W = F-W-W-W > F-W-W. Consequently, the rotations with summer fallow or partial fallow would have inflated ANM more than rotations without summer fallow due to SOM loss if the SOM differences widened since 2003 or, certainly, if organic N differences persisted and ANM was estimated from experiment initiation when soil organic N was equivalent.

The high and low FUE estimated in the GM-W-W and ContW systems, respectively, were due to the low and high quantities of N fertilizer applied to GM-W-W and ContW, respectively. This was in agreement with previous findings where FUE decreased as N fertilizer applied increased (Campbell, Zentner, Selles, McConkey, & Dyck, 1993; Lin & Chen, 2014; Sindelar, Schmer, Jin, Wienhold, & Varvel, 2016). However, unlike most previous studies, we focused on the entire rotation system and not a particular crop in the rotation. The increase in FUE as N fertilizer applied decreased was not always true in this study. For example, FUE for W-C-W-P was higher or equal to that in F-W-W and F-W-W-W in some years, even though the W-C-W-P system received significantly higher rates of N fertilizer. The fact that FUE for fallow systems were only higher than ContW implies that the fallow systems were unable to offset the loss of grain and protein production in the fallow phase, taking into consideration the quantity of N fertilizer used in those systems. For example, in comparison to ContW, GM-W-W used 60% less N fertilizer and had 16% less grain yield, while F-W-W and F-W-W-W used 40 and 29% less N fertilizer and had 17 and 12% less grain yield, respectively. The high FUE for W-C-W-P was largely due to the absence of N fertilizer applied to the pea phase.

The low NUE for GM-W-W indicates that this system was less efficient at utilizing the available N. With only about 20 kg N ha^{-1} yr^{-1} being applied to the GM-W-W system (Table 1), it still had much higher total available N than the other systems, however, the resulting grain and protein yields were among the lowest. It is likely that most of the N actually taken up by wheat in the GM-W-W system, particularly after the GM, was derived from N mineralized from GM above- and below-ground residues, and SOM. This coupled with the absence of crop yield during the GM phase, and low soil moisture in some years (Kröbel et al., 2014), could also explain the low NUE in this system. Other factors may also account for the low NUE in the GM-W-W system including the inability to account for potential N mineralization during the growing season, the fact that no N credit was applied to the last wheat phase as it was unknown, and because the N benefit provided by grain legumes and GM may last for several years (Grant et al., 2016; Kirkegaard & Ryan, 2014; O'Donovan et al., 2014; St. Luce et al., 2015, 2016a).

The higher NUE for ContW than the fallow systems and the partial-fallow GM-W-W system implies that this system was more efficient at utilizing the available N sources. Total available N was similar among ContW and the fallow systems, due to the relatively high incidence of apparent immobilization (negative ANM) in ContW, but ContW had 21 and 14% higher grain yield than F-W-W and F-W-W-W, respectively. The low yield of the fallow systems could also be a reason for their low NUE, in that the grain and protein yield for the crop phases could not compensate for the absence of crop yield in the fallow phase (Campbell et al., 2007b; Fan et al., 2018; McConkey et al., 2002).

One of the major goals of sustainable and intensive cropping is to increase grain and/or protein production per unit of input and area (Garnett et al., 2013). Our study showed that the W-C-W-P system increased grain and protein production above all other systems, and used less N fertilizer than a continuous cereal monoculture, resulting in high FUE. For example, the W-C-W-P used 21% less N fertilizer than ContW, but had 14 and 34% more grain and protein yield, respectively. Compared to the other systems, W-C-W-P used 12, 31, and 96% more N fertilizer than F-W-W-W, F-W-W, and GM-W-W, respectively, but produced 30, 38, and 35% more grain yield, and 56, 66, and 52% more protein yield, respectively. While FUE in our context may not be the most accurate way of determining NUE, the information may be useful to producers where only data on the quantity of N fertilizer applied is readily available (Kröbel et al., 2012). Analyzed from the perspective of NUE, where all available N sources were considered, W-C-W-P was the most efficient for protein yield and the second most efficient for grain yield after ContW. Compared to GM-W-W, W-C-W-P had 4% less total available N, but had 35 and 52% more grain and protein yield, respectively. Compared to the other systems, it had 19 to 25% more available N, and 14 to 30% and 34 to 66% more grain and protein yield, respectively.

5 | CONCLUSIONS

This study showed that diversified cropping systems which include pulses in the rotation can more consistently produce high grain and protein yields, without relying on substantial synthetic N fertilizer inputs than a continuous cereal monoculture system and fallow systems in the semiarid prairies, regardless of growing conditions. The low N fertilizer use and high FUE of the diversified system can potentially minimize the negative environmental consequences associated with N fertilizers. In semiarid regions, where moisture availability is a major constraint to agricultural productivity, traditional summer fallow systems, within the context of the parameters considered in this study, may be warranted going forward, but only if the subsequent crop yield more than compensates for the yield loss in the fallow year. With the need to meet the demands of a rapidly growing world population and future technological developments, such as the genetic enhancements of cultivars for improved heat and drought tolerance, coupled with improved farming practices, the use of continuous cropping over fallow systems, and extended and diversified over monoculture systems is favored.

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