Pulse-included diverse crop rotations improved the systems economic profitability: evidenced in two 4-year cycles of rotation experiments

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Abstract

In the recent past, pulse crops have become increasingly important to agricultural producers as they contribute significantly to the economy. However, the research surrounding the economics of pulse crops is limited. This study determined the net returns and risks of 14 different rotations with various frequencies and sequences of pulse crops and quantified the long-term economic effects. An 8-year field experiment (two 4-year rotation cycles) was carried out at Swift Current, Saskatchewan, and Brooks, Alberta, Canada, during 2010–2019. The crops in the rotation included spring and durum wheat (\textit{Triticum aestivum} L.) (W), field pea (\textit{Pisum sativum} L.) (P), chickpea (\textit{Cicer arietinum} L.) (C), lentil (\textit{Lens culinaris} Medik) (L), and Oriental mustard (\textit{Brassica juncea} L.) (M). Net revenue was estimated and a simulation model was used to conduct the risk-return analysis. Net revenue was significantly different among the 14 rotations, where rotations with either high frequencies of lentil or diverse crops generated the highest net income. More diverse rotations such as P-M-L-W or L-C-P-W provided net income that were statistically comparable to the L-L-L-W rotation and were significantly greater than wheat monoculture systems. Risk analysis suggested that neutral or slightly risk averse producers may select rotations with higher frequencies of lentil, whereas more risk averse producers may prefer more diverse rotations. Inclusion of pulses in a rotation as preceding crops had a positive economic impact on the following non-pulse crops and reduced nitrogen cost by 37\%, which can lead to a low carbon footprint. Long-term studies with comprehensive datasets are rare and here for the first time we had two full 4-year cycles of experimental data for 14 diverse rotations at three sites, enabling us to make sound conclusions—adopting diverse cropping rotations that include pulses, especially lentil, can reduce economic risks and improve farm profitability.

Keywords Cereal-pulse crop rotations \& Input cost \& Net revenue \& Risk analysis

Abbreviations

\begin{tabular}{ll}
N & Nitrogen \\
PC & Pulse crop \\
W & Wheat \\
P & Field pea \\
C & Kabuli chickpea \\
L & Red lentil \\
M & Mustard \\
NR & Net revenue \\
CDF & Cumulative probability distribution function \\
SERF & Stochastic efficiency with respect to a function \\
CE & Certainty equivalents \\
ARAC & Absolute risk aversion coefficient \\
SE & Standard error
\end{tabular}
1 Introduction

Over the past three decades, pulse crops (PC) have become significant in Canadian agriculture and have generated an estimated annual market value of $2.7 billion during 2019–2020 (Agriculture and Agri-Food Canada 2021). The addition of pulse crops to cereal and oilseed production systems provides a variety of agronomic and economic benefits such as improved water use, soil quality, and serve as a break crop for disease, pest, and weed life cycles (Entz et al. 2002; Gan et al. 2011a; Gan et al. 2015; Gustafson and Yildiz 2017; Moussart et al. 2013). More importantly, pulse crops, such as field peas (Pisum sativum L.), chickpeas (Cicer arietinum L.), and lentils (Lens culinaris Medik) have the ability to fix atmospheric nitrogen (N) (Burgess et al. 2012; Hossain et al. 2016); this reduces the amount of supplemental N that farmers must provide for proper growth and development of subsequent crops (Kirkby 1981), creating a reduction in costs and a potential to increase net revenue (NR) (Gan et al. 2011b; Liu et al. 2016). The increased soil N resulting from biological fixation has both economic (Cox et al. 2010) and energy use benefits since over 80% of total energy inputs from traditional grain production systems are made up of N fertilizer and fuel (Zentner et al. 2004). Most importantly, the pulse-included, diversified crop rotations have been shown to improve the agroecosystem’s productivity and robustness (Li et al. 2019; St. Luce et al. 2020), enhance the systems stability and resilience (Liu et al. 2022; St. Luce et al. 2020), and decrease the environmental footprint (Chai et al. 2021; Liu et al. 2022).

To examine the sustainability of crop rotations, it is important to observe them in long-term experiments. Multiple studies have observed that cropping systems with differences in soil quality will take an extended period of time to show differences from each other (Ganeshamurthy 2009; Kelley et al. 2003; Pikula and Rutkowska 2014). Ganeshamurthy (2009) described that many soil quality characteristics in a 16-year experiment were not different between systems with and without pulse crops; however, the author highlighted that the differences between soils under continuous pulse crops and soils under non-pulse crops are slow to accumulate and will take a long time. Pikula and Rutkowska (2014), in a 33-year experiment, observed that a cropping system with legumes and mustard had less degradation of soil organic carbon than a cropping system without legumes and mustard. Kelley et al. (2003) demonstrated that over a lengthy period, when high residue-producing crops, such as wheat, are added to a soybean (Glycine max L.) rotation, there is a higher build-up of carbon in the soil.

Efficient use of crop rotations, instead of monocropping cereal grains, can improve crop yields and quality, thus generating higher revenue (Bezdicek and Granatstein 1989; Gan et al. 2015; Krupinsky et al. 2006). Also, due to the reduced costs associated with N fertilizers from incorporating pulse crops, such as dry peas and lentils, in cereal grain rotations, there are possible economic and risk reduction benefits (Khakbazan et al. 2017a, 2017b, 2020; MacWilliam et al. 2014; Zentner et al. 2004). Results from Cox et al. (2010) support the finding that pulse crops need to provide a substantial portion of N required for following grain crops in order to sustain and improve profits. Zentner et al. (2001) used experimental data from 1979 to 1997 at Swift Current, Saskatchewan, Canada, and demonstrated that wheat-lentil rotations had larger profit benefits with an intermediate level of risk for farmers, while continuous wheat cropping had the highest associated financial risks. They also showed that protein content of wheat was higher, and incidence of diseases was lower in wheat rotated with lentils, as compared to continuous wheat rotation. This implied that diversifying wheat by including lentil to the crop rotation reduced the financial risk (Zentner et al. 2001). In the Canadian prairies, Khakbazan et al. (2009, 2014, 2020) determined that lentils and field peas in rotations with wheat and canola generated a significantly higher NR than continuous cropping of wheat and canola (Brassica napus L.).

There is limited information currently available on the dual benefits (agronomic and economic) of pulse crop frequency and sequence in rotation systems focusing on the long-term impacts. The objectives of this manuscript include (i) assessing the profitability and performance of a variety of pulse crop rotations in comparison with wheat monoculture during an 8-year study period (Fig. 1), (ii) examining the risk of rotations with different types and frequencies of pulse crops, and (iii) determining residual effects of preceding crops on the yield and NR of subsequent crops in rotations.

2 Materials and methods

The experimental design, agronomic management on crops, and data collection of crop performance and yields have been detailed in previous publication (Liu et al. 2020; Li et al. 2019); economic calculations, statistical and risk analysis, and methods and materials have been previously described in detail by Khakbazan et al. (2020); thus, only a summary of the experiment will be provided here.

2.1 Field study

Two 4-year crop rotation cycles composed of cereal crops rotated with a range of pulses and oilseeds at varying frequencies and sequences were established in three locations near the 50° N latitudinal line. Two locations were established at Swift Current, Saskatchewan in 2010 (Swift1) and in 2011 (Swift2), and one location was established at the Crop Diversification Centre South, Brooks, Alberta in 2011 (Brooks). Further
information regarding site coordinates was provided in Khakbazan et al. (2020).

Soil type in all sites was an Orthic Brown Chernozem Soil, with soil texture ranging from loam to silt loam. Growing season (April 1 to September 30) precipitation, air temperature, and the 30-year averages for precipitation and air temperature for all the locations were provided in Khakbazan et al. (2020). A more detailed description of the agronomic components such as crop management and soil sampling was described in Liu et al. (2020).

This experiment used the following species in crop rotation: wheat (Triticum aestivum L., cv. “AC Lillian” and “Transcend Durum”) (W), yellow field pea (Pisum sativum L., cv. “CDC Meadow”) (P), Kabuli chickpea (Cicer arietinum L., cv. “CDC Frontier”) (C), red lentil (Lens culinaris Medik. cv. “CDC Maxim CL”), (L) and Oriental mustard (Brassica juncea L., cv. “Cutlass”) (M).

The treatments consisted of 13 diversified crop rotations and 1 continuous cropping of wheat. For all rotations except for treatment 13, the crop sequence for years 1–4 was repeated for years 5–8. The crop sequence for treatment 13 was C-C-C-W-C-M-C-W. Treatment 1 consisted of two continuous cycles of wheat (W-W-W-W) and was considered the control rotation. The other rotation treatments included (i) 1 year of a pulse species followed by three consecutive years of wheat (rotations 2 and 3: PC-W-W-W), (ii) pulse species alternated with wheat each year (rotations 4–8: PC-W-PC-W), (iii) pulse species alternated with mustard and wheat (rotations 9 and 10: PC-M-PC-W), and (iv) three consecutive years of the same type of pulse crop followed by wheat, or three consecutive years of different types of pulse crops, followed again by wheat (rotations 11–14: PC-PC-PC-W).

The experiment had 56 plots at each location. The treatments were arranged using a randomized complete block design with four replicates at each location (Khakbazan et al. 2020). The spatial dimensions of each plot were 3 m × 12 m at Brooks and 4 m × 12 m at Swift Current.

Soil nutrient concentrations of each plot were measured in the preceding fall, and the following spring at the depth of 0–60 cm before year 1 of the rotations. The residual effect of preceding crops on the growth of the following crops in rotation was assessed.

In the first year of the treatments, all crops were seeded on wheat stubble seedbeds at all three locations. Seeding dates and rates of different crops were provided in Khakbazan et al. (2020). The seeding rate was determined based on the percentage of seed germination, mean seed weight, and the estimated field emergence rate. This was adjusted to reach the target plant population density. Crops were seeded in the first week of May and side banded with ammonium phosphate based on soil test recommendations. All the pulse crops were inoculated with recommended granular Rhizobium inoculants at the time of seeding.

In the first year of the rotation (i.e., year 1 of the first 4-year cycle and year 5 of the second 4-year cycle), N fertilizer was applied to non-pulse crops, including oriental mustard and wheat, on the basis of pre-seeding soil tests and expected crop yields. Thus, the N fertilizer application rates varied for each rotation and at each location. The application methodology was outlined in Khakbazan et al. (2020). In the following years of the rotation, a pre-set blanket N fertilizer rate was applied to non-pulse crops. This allowed the assessment of rotational effects on the N balance in each rotation, enabling the determination of the effects of preceding crops on the...
following crops in the rotation and the entire rotation system effect. For example, if wheat grain yield (or protein yield) after a pulse crop was higher, the additional yield was a result of positive contribution of pulse crops, because both wheat after a pulse or wheat after wheat received the same rate of fertilizer N. This rotational effect would not be determined adequately if wheat after wheat received a N rate different from wheat after a pulse crop. No N fertilizer was applied to pulse crops except a small portion of the N contained in the product of phosphorus fertilizer. Phosphorus (P$_{2}$O$_{5}$) fertilizer application followed Khakbazan et al. (2020) methodology and included the annual soil testing to ensure an adequate amount of phosphorus for all crops. Pesticides used in the study are listed in Table 1. Best crop protection practices recommended for the local regions (Saskatchewan Agriculture 2010-2019) were used as a guild to determine pesticide application rates for each crop. Those application rates for specific crops at a given site were the same regardless of the rotation. Specific type, rate, and timing of pesticide application were adopted in the crop protection program to meet the needs of each crop at each site, including the use of small to zero doses. Additionally, desiccants were applied to pulse crops and mustard at crop maturity each year, and the application rates varied with crops and years. Crops were harvested at full maturity using a plot combine and the harvested grains were cleaned, processed, and a number of grain quality parameters were determined (Khakbazan et al. 2020), including seed yield, plant dry matter, nutrient concentrations, and 1000-seed weight.

### 2.2 Economic calculation

Annual net revenue (NR) values of each rotation system were calculated using the econometric software Eviews (Eviews quantitative software, Version 11 2019) following the methodology described by Khakbazan et al. (2020). The annual NR for each crop and crop rotation was calculated by subtracting production and input expenses from gross revenue as described by Zentner et al. (2002) and Khakbazan et al. (2009). All values were expressed in CAD ha$^{-1}$ for each crop and rotation. Input and output prices used in the economic analysis and initial static crop budgets were determined following the process outlined in Khakbazan et al. (2020). Table 1 provides a summary of input and output prices used in the analysis. Mean values of seed and fertilizer prices from 2010 to 2019 were used for static budgeting (Saskatchewan Agriculture 2010-2019).

Net revenue definition remains unchanged from Khakbazan et al. (2020). Net revenue was defined as the income remaining after paying for all monetary costs, land investment costs and ownership costs on machinery and buildings, and labor. Fixed costs include the cost of depreciation of the equipment due to use and years in service, investment, and housing/insurance costs based on equipment sizes and work rates (Saskatchewan Agriculture 2018). Costs for repair and maintenance, fuel and lubrication, and labor were calculated following the procedure outlined in Khakbazan et al. (2020). A fixed cost per hectare was calculated for fertilizer application and seeding, based on equipment, hours of usage, investment and housing costs, and work rate (Saskatchewan Agriculture 2018). Other field activity costs were also calculated as outlined in Khakbazan et al. (2020).

Application rates of each input were multiplied by the prices of the products, including fertilizer, pesticides, and seed, in order to calculate the total fertilizer, chemical, and seed costs. A similar method was used to calculate the combining and transportation costs from field to farm storage, and from farm to the first point of delivery, with different truck sizes assumed in the calculations (Saskatchewan Agriculture 2018). Various pieces of information were collected regarding the costs of grain trucks, in order to calculate net revenue. The capacity of a grain truck was assumed to be 9.5 tonnes (t) for the field to yard measurement, and $9.5 t^{-1}$ for the first 5 kilometers of travel, plus $0.92 t^{-1}$ for each additional kilometer after that. The capacity of a grain truck was assumed to be 13 tonnes for the farm to first point of delivery measurement, with 100 km of distance, and a speed of 60 km h$^{-1}$. The calculation also incorporated the costs for the auger and associated tractor use, which included the assumption that 20 min were required to load a truck, and 5 min were required to unload said truck.

The interest rate on variable costs was assumed to be represented by a figure of 7%, and no allowance was made for interest costs related to land equity. We set these values on the assumption that all farm machinery works were operated by farmers and other similarly skilled workers and that no custom work costs were included. The labor cost was estimated to be $21 h^{-1}$ for crop production, based on information from the 2019 Saskatchewan agriculture crop planning guide.

The economic analysis included the costs and returns for each crop and each rotation. In this paper, the emphasis was placed on the comparison of the second cycle of the study with the first cycle and the comparison of the entire 8-year results with the first 4 years. The first 4-year cycle results were reported previously (Khakbazan et al. 2020). The residual effect of preceding crops on subsequent crops was also presented. The detailed outcome data recorded for each crop facilitated our determination of the agronomic and economic-based analyses for each rotation system at a farm level.

Sensitivity analysis was conducted to assess how sensitive the cropping rotation systems and the resulting economic outcomes are in response to (1) the change of crop prices based on the long-term price trends and (2) the correlation in crop prices among the different species. There was generally a weak correlation between crop prices (Table 1). Therefore, the following five sensitivity scenarios were examined in
### Table 1

Historical prices of fertilizer, crop seed, and crop product and 2018 pesticide prices at Swift Current location 1 (Swift1) and location 2 (Swift2), Saskatchewan and Brooks, Alberta, Canada. Note: historical prices for fertilizers, seed and crop products were adopted from crop planning guide 2010-2019 published at [http://www.publications.gov.sk.ca/details.cfm?p=83871](http://www.publications.gov.sk.ca/details.cfm?p=83871) and pesticide prices were collected in 2018 from Manitoba pesticide retails. The common name of each pesticide is listed in parentheses. Note: SD standard deviation, CV coefficient of variation.

| Year | Fertilizer price | Seed price ($ kg$^{-1}$) | Crop product price ($ kg$^{-1}$) |
|------|------------------|---------------------------|----------------------------------|
|      | $N$              | $P_2O_5$                  | Spring wheat | Durum wheat | Pea | Lentil | Chickpea | Mustard | Spring wheat | Durum wheat | Pea | Lentil | Chickpea | Mustard |
| 2010 | 0.904            | 0.705                     | 0.287        | 0.331 | 0.285 | 0.882 | 0.683 | 4.960 | 0.175 | 0.166 | 0.214 | 0.617 | 0.507 | 0.683 |
| 2011 | 1.146            | 1.168                     | 0.331        | 0.367 | 0.285 | 0.882 | 0.683 | 4.431 | 0.230 | 0.235 | 0.220 | 0.551 | 0.595 | 0.507 |
| 2012 | 1.147            | 1.257                     | 0.402        | 0.452 | 0.358 | 0.573 | 0.838 | 3.527 | 0.219 | 0.257 | 0.178 | 0.397 | 0.728 | 0.529 |
| 2013 | 1.323            | 1.102                     | 0.386        | 0.404 | 0.404 | 0.705 | 0.705 | 3.748 | 0.263 | 0.270 | 0.312 | 0.441 | 0.595 | 0.595 |
| 2014 | 1.058            | 0.970                     | 0.331        | 0.340 | 0.386 | 0.661 | 0.705 | 3.748 | 0.211 | 0.230 | 0.257 | 0.441 | 0.485 | 0.595 |
| 2015 | 1.186            | 1.173                     | 0.254        | 0.417 | 0.287 | 0.690 | 0.375 | 3.616 | 0.225 | 0.225 | 0.222 | 0.529 | 0.419 | 0.551 |
| 2016 | 1.186            | 1.173                     | 0.271        | 0.333 | 0.419 | 1.206 | 0.448 | 1.166 | 0.241 | 0.260 | 0.321 | 0.728 | 0.353 | 0.816 |
| 2017 | 0.897            | 0.994                     | 0.516        | 0.642 | 0.529 | 1.140 | 0.816 | 8.819 | 0.221 | 0.246 | 0.279 | 0.661 | 0.661 | 0.617 |
| 2018 | 1.011            | 1.036                     | 0.478        | 0.551 | 0.496 | 0.838 | 1.874 | 9.480 | 0.256 | 0.256 | 0.246 | 0.358 | 0.409 | 0.621 |
| 2019 | -                | -                         | -            | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     |
| Mean | 1.132            | 1.064                     | 0.362        | 0.426 | 0.383 | 0.842 | 0.792 | 4.833 | 0.235 | 0.240 | 0.276 | 0.508 | 0.510 | 0.613 |
| SD   | 0.190            | 0.164                     | 0.092        | 0.107 | 0.090 | 0.215 | 0.434 | 2.661 | 0.018 | 0.030 | 0.036 | 0.131 | 0.131 | 0.087 |
| CV   | 16.78            | 15.41                     | 25.41        | 25.12 | 23.50 | 25.53 | 54.80 | 55.06 | 7.66  | 12.50 | 13.04 | 25.79 | 25.69 | 14.19 |

**Pesticide Price Table**

| Pesticide          | Price ($ kg$^{-1}$ or L$^{-1}$) | Price ($ kg$^{-1}$ or L$^{-1}$) |
|--------------------|----------------------------------|----------------------------------|
| 2,4-D 600          | 10.00                            | 27.10                            |
| Achieve (tralkoxydim) | 47.60                           | 128.00                           |
| Assure II           | 20.00                            | 179.20                           |
| Authority (sulfentrazone) | 166.80                        | 2334.30                          |
| Bonanza (trifluralin) | 1.00                            | 139.10                           |
| Bravo 500           | 9.40                             | 129.60                           |
| Buctril M           | 27.00                            | 29.00                            |
| Decis (deltamethrin) | 98.00                            | 26.00                            |
| Headline EC         | 92.30                            | 1413.50                          |
| Heat (saflufenacil)  | 40.70                            | 7.92                             |

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detail: (1) All crop prices increased or decreased by 10% and 20%. 2) Since wheat prices were not strongly correlated with the prices of other crops, only wheat prices increased or decreased by 10% and 20% but the prices of other crops remained constant. (3) Pea and wheat prices increased or decreased by 10% and 20% but the prices of other crops remained constant, because there was a weak correlation between pea and other crops. (4) Prices of lentil and chick-pea increased or decreased by 10% and 20% but the prices of other crops remained constant, because there was a weak correlation between these two and other crops. (5) Price of mustard increased or decreased by 10% and 20% but the prices of other crops remained constant, because there was a weak correlation between mustard and other crops.

2.3 Statistical analysis

The analysis included the yearly NRs for each crop individually, as well as the entire rotation from 2010 to 2019. A three-factor (site × rotation cycle × rotation) ANOVA was performed using PROC MIXED (SAS Institute Inc. 2014a, 2014b) to determine the effect of site, rotation cycle, and crop rotation on the NRs. The site, rotation cycle, and crop rotation were considered to be fixed factors with fixed effects, while replicates were considered to be a random factor with random effect. The procedure is a repeated measure because the two rotation cycles were not independent.

A two-factor (rotation cycle × rotation) ANOVA was performed using PROC MIXED (SAS Institute Inc. 2014a, 2014b) to determine the effect of rotation cycle and crop rotation on the NRs for each site. In this procedure, rotation cycle and crop rotation were considered to be fixed factors with fixed effects, while replicates were considered to be a random factor with random effect. Tukey’s method was used to test differences in the NRs between rotation cycle and between rotations. At $P > 0.05$, the difference was not statistically significant.

Since we have published the effect of crop rotations on the NRs for the first 4-year cycle (Khakbazan et al. 2020), the crop rotation effects on the NRs for each site were only performed for the second cycle (years 5–8). In this procedure, crop rotation was considered to be a fixed factor with fixed effect, while replicates were considered to be a random factor with random effect.

The mixed model procedure in SAS (SAS Institute Inc. 2014a, 2014b) was also used to determine the impact of different preceding crops on yields and NRs of the following wheat crop at each site. In this procedure, different preceding crops were considered a fixed factor with fixed effect, whereas replicates were considered to be a random factor with random effect. Yield and NR of wheat followed by different preceding crops were respectively compared using Tukey’s method, and the effect on yield and NR was considered significant at $P < 0.05$ for each site.

2.4 Risk analysis

Stochastic budgets of NRs were developed for all crops to generate profitability distributions of NR for the different rotations. Microsoft Excel add-in Simulation and Econometrics to Analyze Risk (SIMETAR), developed by Richardson et al. (2004), was used to simulate 500 iterations of crop yield, production cost, and crop price distributions for each individual crop in each rotation at three experimental locations. Yields for each crop in each rotation and prices were drawn from a multivariate empirical distribution, and then used to calculate simulated yearly revenues (years 1–8). Simulated yields were developed using experimental yields for each crop in each rotation; therefore, the impacts of preceding crops were accounted for in the yield distributions. Crop price distributions were developed based on 2010–2019 crop prices (Saskatchewan Agriculture 2010–2019 Saskatchewan agriculture crop planning guide). Crop production costs based on the agronomic management practices of crops in each rotation from 2010 to 2019, average 2010–2018 seed and fertilizer costs, and 2018 costs for other inputs, were all subtracted from simulated gross revenues to obtain the expected NR. Although 2018 or average (2010–2018) input costs that were used to estimate costs were deterministic, field crop management activities varied depending on the year and the crop. Therefore, an empirical distribution derived from 8 years of costs was used to simulate costs for each crop. Therefore, 500 simulated yearly NR values (years 1–8) were calculated by subtracting the simulated production cost from the simulated gross revenue for each crop in each rotation and at each location (Richardson et al. 2000; Richardson et al. 2008). SIMETAR was used to construct a cumulative distribution function (CDF) from simulated NR with probability ranging from 0.0 to 1.0. Additionally, the simulated NR values were used to determine the certainty equivalents (CE) to evaluate the rotation strategies under risk (Richardson et al. 2008).

Stochastic efficiency with respect to a function (SERF) was used to evaluate utility-efficient alternative rotations (Hardaker and Lien 2010; Hardaker et al. 2004; Richardson et al. 2008). SERF identifies the most efficient alternatives for a range of risk preferences by ranking alternatives in terms of CE (Richardson et al. 2008). For a given level of absolute risk aversion coefficient (ARAC), the CE is calculated using the negative exponential equation defined by Pratt (1964) and Hardaker et al. (2004) as $r_{\lambda}(w) = - u''(w)/u'(w)$, which represents the ratio of the second and first derivatives of the decision-maker’s utility function, $u(w)$. The $r_{\lambda}(w)$ is risk aversion coefficient and $w$ is a measure of wealth. The negative exponential utility function assumes decision-makers prefer less risk to more given the same expected return and they have...
constant absolute risk aversion (i.e., they view a risky strategy for a specific level of risk aversion the same without regard for their level of wealth). The CE is a measure of a certain payoff that a producer would have to receive to be indifferent between the certain payoff and the payoff of a riskier rotation (Hardaker et al. 2004). The higher CE with the same level of ARAC corresponds to a preferred management option.

The ARAC was estimated for an upper bound of 4/average simulated NR ($645 ha$−$1$) of all 14 rotations at three locations (Hardaker et al. 2004). The ARAC ranged from 0 (risk neutral) to 0.006 (upper bound, highly risk averse) for all 14 rotations at three locations. The CE was then used to evaluate the rotation strategies under risk.

3 Results and discussions

3.1 Annual rotation cost

At Swift1, the average annual production cost of the baseline - rotation 1 (W-W-W-W) was $748 y$−$1$ ha$−$1$, and the highest average annual production cost was $882 y$−$1$ ha$−$1$ for rotation 13 (C-C-C-W-C-M-C-W), which is an 18% increase from the baseline. For the continuous wheat treatment (treatment 1), the cost of seed, fertilizer, pesticide, and machinery was $45, $91, $165, and $282 y$−$1$ ha$−$1$, respectively (Table 2). Depending on the type and frequency of pulse crops in a rotation, the costs associated with fertilizers were reduced by up to 38%, and pesticide costs increased by up to 64% in comparison with the baseline (Table 2). It should be noted that rotations containing chickpea often had higher costs due to higher usage of pesticides against Ascochyta blight, a leaf/stem fungal disease caused by Ascochyta rabiei (Banniza et al. 2011). The results from the two 4-year rotation cycles had a trend of effects similar to that found in the first cycle (Khakbazan et al. 2020).

Reduction in N fertilizer use supports the existing literature, in that adding pulse crops to crop rotations not only fixes atmospheric N, but also reduces production costs and the carbon footprint (Cox et al. 2010; Gan et al. 2011b; Kirkby 1981; Liu et al. 2016; Zentner et al. 2004). MacWilliam et al. (2018) used a meta-analytic approach comparing greenhouse gas (GHG) emissions of pulse-containing and pulse-free crop rotations in western Canada and concluded that, in general, cereal and oilseed crops grown after pulse crops (e.g., dry pea or lentil crop) had similar or reduced GHG emissions compared to those grown after a cereal or oilseed. They, however, showed that in 2-year cereal or oilseed rotations, the inclusion of pulses reduced GHG emissions compared to all reference rotations, mostly as a result of the reduced synthetic N requirements of the whole rotation. Zentner et al. (2004) showed that N fertilizer and fuel in traditional grain production systems is made up of 80% of the total energy inputs and our study showed that adding pulse crops to the rotation can reduce N fertilizer by 38%. There was a negative impact of increased use of pesticides, but this in terms of the carbon footprint as compared to N fertilizer is negligible, because pesticide use accounts for a small proportion of the total GHG emissions (Gan et al. 2014). Increases in pesticide use may have more significant implications in terms of water quality or other environmental parameters, but that depends on the specific environment condition and the landscape. Additionally, wheat grown after a pulse crop had higher protein concentration in the grain, providing protein premium to producers. Also, there are sustainability benefits for wheat grown after pulses in rotation with improved soil fertility and carbon concentration, as well as increased water availability, and enhanced soil microbial benefits (Bainard et al. 2017; Hamel et al. 2018; Li et al. 2019; Liu et al. 2022). We did not address these effects in the present study.

Swift2 had similar costs to Swift1, with an average annual production cost of rotation 1 being $749 y$−$1$ ha$−$1$. Averaged across the two 4-year rotation cycles, the costs for the baseline were $46, $91, $164, and $283 y$−$1$ ha$−$1$, for seed, fertilizer, pesticide, and machinery costs, respectively (Table 2). Depending on the frequencies of pulse crops in rotation, fertilizer costs were reduced by up to 37%, while pesticide costs increased by up to 74% compared to the baseline rotation. The average annual costs increased by up to 22% from the continuous wheat, with the highest average annual production cost being $918 y$−$1$ ha$−$1$ for rotation 13 (Table 2). Labor costs were also increased for rotations with a higher frequency of pulse crops (Table 2). The cost ranking of the rotations in the two 4-year cycles is similar to the first 4-year cycle (Khakbazan et al. 2020).

The associated costs at Brooks were slightly lower compared to both the Swift1 and Swift2 sites. For the continuous wheat treatment, the average annual production cost across the two 4-year cycles was $698 y$−$1$ ha$−$1$. In comparison, the highest average annual production cost appeared in rotation 13 with a value of $836 y$−$1$ ha$−$1$ (Table 2), which is a 20% increase relative to rotation 1. When some of these costs are broken down into different categories, the costs for the continuous wheat treatment are $24, $85, $131, and $289 y$−$1$ ha$−$1$, for seed, fertilizer, pesticide, and machinery costs, respectively (Table 2). Depending on the rotations, fertilizer costs were reduced by up to 35% and pesticide costs increased by up to 72% from the baseline rotation. As with Swift1 and Swift2, there was a general trend of increasing costs associated with a higher frequency of pulse crops in a rotation (Table 2).

Both machinery and labor costs between rotations were not as variable as some of the other costs, such as pesticides. Pesticides were frequently the second largest expense out of the categories presented in Table 2, being 64–74% greater than the control for rotation 13 in the two 4-year cycles (Table 2). At all sites, the addition of pulse crops into rotations
Table 2  Average annual cost of two 4-year rotation cycles at Swift Current site 1 (Swift1) and site 2 (Swift2), Saskatchewan and Brooks, Alberta, Canada.

| Crop rotation (yr1-yr2-yr3-yr4) | Seed | Fertilizer | Pesticide | Machinery | Labor | Other | Total cost |
|----------------------------------|------|------------|-----------|-----------|-------|-------|------------|
|                                  | $ yr^{-1} ha^{-1} %&dagger; | $ yr^{-1} ha^{-1} %&dagger; | $ yr^{-1} ha^{-1} %&dagger; | $ yr^{-1} ha^{-1} %&dagger; | $ yr^{-1} ha^{-1} %&dagger; | $ yr^{-1} ha^{-1} %&dagger; | $ yr^{-1} ha^{-1} %&dagger; |
| Swift1                           |      |            |           |           |       |       |            |
| 1: W-W-W-W                       | 45   | 0  | 91  | 0  | 165  | 0   | 282  | 0  | 24  | 0  | 142  | 0  | 748  | 0 |
| 2: P-W-W-W                       | 49   | 9  | 75  | -17 | 162  | -2  | 291  | 3  | 26  | 6  | 138  | -3 | 739  | -1|
| 3: C-W-W-W                       | 73   | 64 | 77  | -16 | 186  | 13  | 293  | 4  | 26  | 7  | 139  | -2 | 793  | 6 |
| 4: P-W-P-W                       | 53   | 19 | 66  | -27 | 196  | 19  | 301  | 7  | 28  | 13 | 135  | -5 | 778  | 4 |
| 5: P-W-L-W                       | 49   | 9  | 68  | -25 | 211  | 28  | 295  | 5  | 26  | 9  | 132  | -7 | 781  | 4 |
| 6: L-W-C-W                       | 75   | 67 | 70  | -23 | 227  | 38  | 285  | 1  | 25  | 2  | 129  | -9 | 810  | 8 |
| 7: L-W-L-W                       | 45   | 2  | 70  | -23 | 218  | 32  | 287  | 2  | 25  | 3  | 128  | -9 | 773  | 3 |
| 8: C-W-C-W                       | 102  | 130| 70  | -23 | 245  | 48  | 290  | 3  | 25  | 5  | 131  | -8 | 862  | 15 |
| 9: P-M-C-W                       | 74   | 66 | 68  | -25 | 232  | 41  | 292  | 3  | 26  | 6  | 131  | -7 | 823  | 10|
| 10: P-M-L-W                      | 45   | 0  | 68  | -25 | 223  | 35  | 293  | 4  | 26  | 7  | 131  | -8 | 784  | 5 |
| 11: P-P-P-W                      | 59   | 32 | 56  | -38 | 204  | 24  | 303  | 7  | 28  | 15 | 128  | -10| 778  | 4 |
| 12: L-L-L-W                      | 46   | 4  | 61  | -32 | 233  | 41  | 285  | 1  | 24  | 1  | 119  | -16| 769  | 3 |
| 13: C-C-C-W                      | 116  | 160| 65  | -28 | 270  | 64  | 283  | 0  | 24  | 0  | 124  | -13| 882  | 18|
| 14: L-C-P-W                      | 81   | 83 | 60  | -34 | 241  | 46  | 295  | 5  | 26  | 9  | 125  | -12| 828  | 11|
| Swift2                           |      |            |           |           |       |       |            |
| 1: W-W-W-W                       | 46   | 0  | 91  | 0  | 164  | 0   | 283  | 0  | 24  | 0  | 141  | 0  | 749  | 0 |
| 2: P-W-W-W                       | 51   | 11 | 75  | -17 | 179  | 9   | 291  | 3  | 26  | 6  | 137  | -3 | 759  | 1 |
| 3: C-W-W-W                       | 76   | 66 | 77  | -16 | 209  | 27  | 292  | 3  | 26  | 6  | 139  | -2 | 817  | 9 |
| 4: P-W-P-W                       | 55   | 21 | 66  | -27 | 183  | 11  | 299  | 6  | 27  | 11 | 133  | -6 | 763  | 2 |
| 5: P-W-L-W                       | 52   | 14 | 68  | -25 | 193  | 17  | 294  | 4  | 26  | 8  | 131  | -7 | 764  | 2 |
| 6: L-W-C-W                       | 73   | 60 | 70  | -23 | 234  | 42  | 289  | 2  | 25  | 4  | 129  | -9 | 820  | 9 |
| 7: L-W-L-W                       | 48   | 4  | 70  | -23 | 207  | 26  | 286  | 1  | 25  | 1  | 127  | -10| 761  | 2 |
| 8: C-W-C-W                       | 102  | 124| 70  | -23 | 250  | 52  | 293  | 4  | 26  | 7  | 133  | -6 | 873  | 17|
| 9: P-M-C-W                       | 70   | 53 | 68  | -25 | 229  | 39  | 293  | 4  | 26  | 7  | 133  | -6 | 819  | 9 |
| 10: P-M-L-W                      | 44   | -3 | 68  | -25 | 202  | 23  | 288  | 2  | 25  | 3  | 129  | -9 | 756  | 1 |
| 11: P-P-P-W                      | 60   | 32 | 57  | -37 | 197  | 20  | 307  | 9  | 29  | 17 | 129  | -8 | 779  | 4 |
| 12: L-L-L-W                      | 48   | 5  | 62  | -31 | 240  | 46  | 287  | 2  | 25  | 2  | 120  | -15| 782  | 4 |
| 13: C-C-C-W                      | 112  | 146| 66  | -27 | 286  | 74  | 296  | 5  | 26  | 9  | 131  | -7 | 918  | 22|
| 14: L-C-P-W                      | 80   | 76 | 61  | -33 | 227  | 38  | 293  | 4  | 26  | 7  | 123  | -13| 810  | 8 |
| Brooks                           |      |            |           |           |       |       |            |
| 1: W-W-W-W                       | 24   | 0  | 85  | 0  | 131  | 0   | 289  | 0  | 25  | 0  | 144  | 0  | 698  | 0 |
| 2: P-W-W-W                       | 33   | 41 | 73  | -14 | 155  | 18  | 296  | 2  | 27  | 5  | 140  | -3 | 724  | 4 |
| 3: C-W-W-W                       | 57   | 143| 73  | -14 | 162  | 24  | 294  | 2  | 26  | 3  | 139  | -4 | 752  | 8 |
| 4: P-W-P-W                       | 43   | 82 | 64  | -24 | 166  | 27  | 294  | 2  | 26  | 4  | 131  | -9 | 724  | 4 |
| 5: P-W-L-W                       | 39   | 66 | 64  | -24 | 162  | 24  | 293  | 1  | 26  | 2  | 130  | -10| 714  | 2 |
Pulse-included diverse crop rotations improved the systems economic profitability: evidenced in two 4-year...

Table 2

| Seed | Fertilizer | Pesticide | Machinery | Labor | Other | Total cost |
|------|------------|-----------|-----------|-------|-------|------------|
|      | $\text{yr}^{-1} \text{ha}^{-1}$ | $\text{yr}^{-1} \text{ha}^{-1}$ | $\text{yr}^{-1} \text{ha}^{-1}$ |       | $\text{yr}^{-1} \text{ha}^{-1}$ | $\text{yr}^{-1} \text{ha}^{-1}$ |
| 6: L-W-C-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 7: L-W-L-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 8: C-W-C-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 9: P-M-C-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 10: P-M-L-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 11: P-P-P-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 12: L-L-L-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 13: C-C-C-W | 287 | 199 | 52 | 1 | 26 | 129 |
| 14: L-C-P-W | 287 | 199 | 52 | 1 | 26 | 129 |

† W wheat, C chickpea, M field pea, L lentil, M mustard. Crop sequence for the second 4-year cycle (years 5–8) is repeated on the first 4-year cycle except for rotation 13. Crop sequence for rotation 13 is C-W-C-W for the first cycle and C-M-C-W for the second cycle.

‡ Other cost includes costs for crop transportation from field to storage and from storage to the first point of delivery, storage, land tax, miscellaneous, and interest on variable costs.

§ % change to continuous wheat rotation (rotation 1) was calculated for rotations 2 to 14. Note: We assume that all farm machinery works were operated by farmers and no custom work and hired labor costs were included. Crop insurance, utilities, and property taxes were not included in the total cost for each rotation.

3.2 Net revenue analysis

ANOVA analysis showed that the three-factor interaction (site × rotation cycle × rotation) was statistically significant ($P < 0.0001$, Table 3). The interaction between site and rotation was significant, indicating that rotations were affected by the site (Table 3). Since site and rotation were considered to be fixed factors, we presented results for each site separately.

There were twelve rotations at Swift1, twelve at Swift2, and seven at Brooks that performed better than the control, when combining the two rotation cycles (Figs. 2b, 2b, 2f).

At Swift1, for the second 4-year cycle (years 5–8), the best performing rotations were rotations 12 (L-L-L-W), 10 (P-M-L-W), 7 (L-W-L-W), 9 (P-M-C-W), and 5 (P-W-LW) while the worst performing rotations were rotations 1 (W-W-W-W), 13 (C-C-C-W-C-M-C-W), 2 (P-W-W-W), 11 (P-P-P-W), 8 (C-W-C-W), and 4 (P-W-P-W) (Fig. 2a). Rotation 12 had high frequencies of lentils and rotation 10 was more diverse, with both being the rotations that generated the most NR (Fig. 2a). The NR of rotations 10 and 12 were statistically comparable, but the standard error (SE) for the NR of rotation 12 was 150% higher than that for Rotation 10, suggesting that a more diversified rotation is more stable in terms of net revenue than a rotation with a high frequency of a single pulse crop. The worst performing rotations in NR had high frequencies of chickpeas and continuous wheat, largely because of the infestation of *Ascochyta* disease in chickpea and higher fertilizer input in continuous wheat. Overall, when the results of the two 4-year cycles are combined (years 1–8), rotations that have a higher frequency of lentils (rotations 12 and 7) or a higher degree of diversity (rotation 10), had the highest NR, while the rotations with chickpeas or continuous wheat performed the worst with the lowest NR values (Fig. 2b).

These results are consistent with previous studies which observed that legume inclusion in crop rotations lowers the optimum N rate (Cox et al. 2010; St Luce et al. 2015), improves crop yields (Lafond et al. 2011; O’Donovan et al. 2014), and increases economic returns (Khakbazan et al. 2014; MacWilliam et al. 2014; Zentner et al. 2002). The combined two 4-year cycle results were also consistent with the results of the first cycle (Khakbazan et al. 2020), which showed that higher frequencies of lentils in rotations generated higher NRs (Fig. 2b). The observed economic benefits of
field pea in rotation were lower than expected (Fig. 2b). The NRs for rotations that included field pea were negative, despite the low SEs associated with high frequencies of field pea. When only field pea was added into rotations, there was an improvement in NR; however, in comparison with other pulse crops, the magnitude of this improvement was not large.

Table 3 ANOVA P values for average net revenue ($ ha\(^{-1}\)) of entire rotation as affected by site (Swift Current site 1 and site 2, Saskatchewan and Brooks, Alberta, Canada), rotation cycle (first 4-year cycle and second 4-year cycle), and crop rotation (14 rotations).

| Site     | P value | Site     | Effect                  | P value | Site     | Effect                  | P value |
|----------|---------|----------|-------------------------|---------|----------|-------------------------|---------|
| Swift1   | <0.0001 | Swift1   | Rotation cycle          | <0.0001 | Site     | Rotation cycle          | <0.0001 |
| Swift2   | <0.0001 | Swift2   | Rotation cycle          | <0.0001 | Rotation | Site × rotation cycle   | <0.0001 |
| Brooks   | <0.0001 | Brooks   | Rotation cycle × rotation| <0.0001| Rotation  | Rotation cycle × rotation| 0.0022  |
|          |         | Swift2   | Rotation cycle          | 0.7572  | Site × rotation | Site × rotation × rotation | <0.0001 |
|          |         | Brooks   | Rotation cycle          | <0.0001 | Rotation  | Site × rotation × rotation | <0.0001 |
|          |         | Brooks   | Rotation cycle × rotation| <0.0001| Rotation  | Site × rotation × rotation | <0.0001 |

For example, rotation 2 (P-W-W-W) did not perform significantly better than the continuous wheat in terms of NR. Other studies showed that field peas incorporated into rotations with cereal crops may increase economic returns (Khakbazan et al. 2014; Lafond et al. 2011; St Luce et al. 2015). Liu et al. (2020) also showed that field pea preceding wheat allowed for the...
most agronomic benefits compared with lentil and chickpea. For rotations that included chickpea, as the frequency of chickpea increased, the NRs decreased while the SEs increased (Fig. 2b). Rotation 13, which included the high frequencies of chickpea, did not perform well at Swift1 due to the severe incidence of Ascochyta blight in year 3 (e.g., chickpea yield at 902 kg ha⁻¹). At Swift1 and over two 4-year cycles, the SEs of the NRs were higher in rotations with higher frequencies of chickpea or lentil compared with other rotations (Fig. 2b). The SE of rotation 12 was among the highest SEs. The main source of higher SE of rotation 12 was variability of lentil yield over eight years in Swift1, as indicated by the high coefficient of variation (CV) in Table 4. This indicates that rotations with higher frequencies of lentils can generate higher NRs, but the higher frequencies also increase the variation of NRs compared with other rotations.

At Swift2, for the second 4-year cycle (years 5–8), the best NR generating rotations were rotations 12, 13, 7, 3 (C-W-W-W), 6 (L-W-C-W), and 14 (L-C-P-W), while the worst rotations were the continuous wheat and rotations with high frequencies of field pea. Overall, rotations with either high frequencies of lentils or diverse crops performed the best (Fig. 2d). While rotation 13 did not perform well at Swift1, it did well at Swift2. The observed low yield of chickpea due to the severe incidence of Ascochyta blight in year 3 at Swift1 was not seen at Swift2 (Fig. 2d).

At Brooks, for the second 4-year cycle (years 5–8), the rotations that generated the most NR were rotation 14, and the rotations with high frequencies of lentil or chickpea (Fig. 2e). Rotations including chickpea performed well in the second 4-year cycle and overall, largely due to low incidence of Ascochyta blight at Brooks. Over the two cycles, Rotation 14 provided a NR that was statistically and numerically similar to Rotation 12 (Fig. 2f). Additionally, the SE of rotation 14, which included diverse crops, was nearly 63% lower than the SE of rotation 12. Again, the variability of lentil yield over the years of study at this site was the main source of higher SE of rotation 12 (Table 4). The rotations which generated the lowest NRs during the 8-year study period were the baseline rotation and those with high frequencies of field pea. Overall, at Brooks, rotations that have either a higher frequency of lentil or more diversified rotations had the highest NR, while the baseline and rotations with high frequencies of field pea were the rotations which generated the lowest NRs.

There were differences in NRs between the first 4-year and the second 4-year cycles at Swift1 and Brooks, but not at Swift2 (Figs. 2). For a detailed analysis of the first 4-year cycle, refer to Khakbazan et al. (2020). The NR differences between rotation cycles might be related to weather in a given rotation cycle. Precipitation affects biological N fixation at the pulse crop phase, and affects N availability at the non-pulse crop phases. Overall, these differences show that crop performance can change over time, depending on a wide variety of factors such as pesticide management and varying weather conditions.

The effects of five crop price change scenarios (as described in Section 2) on NR for each rotation at each site-year were determined, and the results revealed that in general the ranking and profitability of the 14 rotations remained unchanged within the assumed -20 to +20% price range (data not shown). However, if changes among crop prices are significant or if single year crop prices are used instead of average crop prices from 2010 to 2019, the ranking of rotation will be affected and may change the overall NR ranking of rotations at each site. For example, at Swift1, when prices of wheat and field pea increased by 20% (scenario 3) or prices of chickpea and lentil decreased by 20% (scenario 4), rotation 5 (P-W-L-W) which was originally ranked fourth, became the top three rotations, although statistically, it was not significantly different from rotations 12, 10, and 7. Similarly at the same site, when prices of wheat and field pea increased by 10 or 20% (scenario 3) or prices of chickpea and lentil decreased by 10 or 20% (scenario 4), rotation 10 (P-M-L-W) which was originally ranked second, became first, and performed only numerically better than Rotation 12.

3.3 Residual effect of preceding crops on wheat

Residues from preceding pulse crops significantly influenced the yield and annual NR of the subsequent wheat crops (Table 5). At Swift1 and Swift2, the yields of wheat in year 2 for rotations 2 to 8 (PC-W-W-W and PC-W-PC-W) were 34% and 16%, respectively, higher when the preceding crops were chickpea, lentil, or field pea compared to the wheat monocrop system (Khakbazan et al. 2020). At Swift1 and Swift2 in year 6, wheat yields after pulse crops and following wheat were statistically the same, but wheat after pulse crops was numerically 9% higher than wheat after wheat. For rotations 2 to 8, the type of pulse crop that preceded wheat was irrelevant to the performance of wheat in year 2 and year 6. At Brooks in year 2, the yields and NRs of wheat among rotations 1 to 8 were not statistically different when the preceding crops were either pulses or wheat. At Brooks in year 6, wheat preceded by field pea in rotations 2 (P-W-W-W) and 4 (P-W-P-W) had significantly higher yields and NRs than wheat preceded by chickpea in rotation 8 (C-W-C-W). Besides these observations, many other effects on subsequently planted wheat from preceding pulse crops were described by Liu et al. (2020). It should be noted, that year by year field activities, most notably pesticide use and application, were different between years and sites, which in turn affected costs and NRs.
Table 4  Mean, standard deviation (SD) and coefficient of variation (CV) for crop yield ($ ha\(^{-1}\)) and net return (NR) of all rotations at Swift Current site 1 and site 2, Saskatchewan and Brooks, Alberta, Canada. In the first year of study, all crops were seeded on wheat stubble seedbeds across three sites.

| Crop            | Yield and net revenue | Rotation year | Mean  | SD   | CV (%) |
|-----------------|-----------------------|---------------|-------|------|--------|
|                 |                       | 1             | 2     | 3    | 4      | 5     | 6     | 7     | 8      |
|                 |                       | Mean          | SD    | CV   |
| Swift1          | Chickpea Yield (kg ha\(^{-1}\)) | 1199          | 2108  | 1603 | 2601   | 817   | 2239  | 1761  | 676    | 38     |
|                 | NR ($ ha\(^{-1}\))    | -388          | -144  | -291 | -210   | -512  | -37   | -194  | 260    | -      |
|                 | Lentil Yield (kg ha\(^{-1}\)) | 1050          | 2025  | 1778 | 2291   | 1067  | 3537  | 1958  | 923    | 47     |
|                 | NR ($ ha\(^{-1}\))    | -198          | 255   | 64   | 406    | -157  | 859   | 205   | 396    | -      |
|                 | Field pea Yield (kg ha\(^{-1}\)) | -1339         | -     | -    | 1185   | -     | -     | 1262  | 109    | 9      |
|                 | NR ($ ha\(^{-1}\))    | -18           | -     | -    | 197    | -     | -     | 108   | 127    | -      |
|                 | Wheat Yield (kg ha\(^{-1}\)) | 3632          | 3404  | 2623 | 3015   | 1777  | 4537  | 3165  | 938    | 30     |
|                 | NR ($ ha\(^{-1}\))    | 56            | -30   | -209 | -106   | -340  | 83    | -91   | 162    | -      |
|                 | Mustard Yield (kg ha\(^{-1}\)) | 2273          | 2840  | 2119 | 2501   | 3261  | 2282  | 3752  | 2339   | 2671   |
|                 | NR ($ ha\(^{-1}\))    | 231           | -58   | -122 | -73    | -44   | -138  | 117   | -72    | -78    |
| Swift2          | Chickpea Yield (kg ha\(^{-1}\)) | 3051          | 1907  | 2124 | 3738   | 1462  | 1373  | 2276  | 935    | 41     |
|                 | NR ($ ha\(^{-1}\))    | 440           | -146  | -116 | 781    | -180  | -248  | 88    | 421    | -      |
|                 | Lentil Yield (kg ha\(^{-1}\)) | 1249          | 1971  | 2530 | 3300   | 1636  | 1528  | 2036  | 759    | 37     |
|                 | NR ($ ha\(^{-1}\))    | -127          | 153   | 535  | 817    | 57    | 39    | 246   | 357    | -      |
|                 | Field pea Yield (kg ha\(^{-1}\)) | 1037          | -     | -    | 883    | -     | -     | 960   | 109    | 11     |
|                 | NR ($ ha\(^{-1}\))    | -25           | -     | -    | -193   | -     | -     | -109  | 119    | -      |
|                 | Wheat Yield (kg ha\(^{-1}\)) | 3023          | 2622  | 3999 | 4906   | 1883  | 1749  | 3030  | 1232   | 41     |
|                 | NR ($ ha\(^{-1}\))    | -113          | 215   | 103  | 238    | -384  | -357  | -121  | 250    | -      |
|                 | Mustard Yield (kg ha\(^{-1}\)) | 2589          | 2338  | 2373 | 2688   | 3451  | 2284  | 1282  | 2701   | 2463   |
|                 | NR ($ ha\(^{-1}\))    | -126          | 80    | 196  | 7      | 26    | -234  | -339  | -23    | -121   |
| Brooks          | Chickpea Yield (kg ha\(^{-1}\)) | 3380          | 2276  | 2451 | 1763   | 3548  | 1296  | 2452  | 884    | 36     |
|                 | NR ($ ha\(^{-1}\))    | 768           | 229   | 131  | 138    | 998   | -97   | 361   | 425    | -      |
|                 | Lentil Yield (kg ha\(^{-1}\)) | 3165          | 2737  | 2299 | 1175   | 1696  | 1091  | 2027  | 847    | 42     |
|                 | NR ($ ha\(^{-1}\))    | 848           | 688   | 461  | -4     | 248   | -11   | 372   | 357    | -      |
|                 | Field pea Yield (kg ha\(^{-1}\)) | -2007         | -     | -    | -1301  | -     | -     | 1654  | 499    | 30     |
|                 | NR ($ ha\(^{-1}\))    | -518          | -     | -    | -185   | -     | -     | 351   | 236    | -      |
|                 | Wheat Yield (kg ha\(^{-1}\)) | 4027          | 3167  | 2830 | 1668   | 2374  | 1473  | 2590  | 959    | 37     |
|                 | NR ($ ha\(^{-1}\))    | 147           | 11    | -73  | -237   | -107  | -277  | -90   | 157    | -      |
|                 | Mustard Yield (kg ha\(^{-1}\)) | 3595          | 3105  | 3762 | 3083   | 2043  | 4065  | 1832  | 2155   | 2955   |
|                 | NR ($ ha\(^{-1}\))    | 145           | 5     | 120  | 67     | -122  | 230   | -146  | -105   | 24     |

Wheat yields following wheat in rotations 1, 2, and 3 in both year 3 and year 7 were the same, except at Swift1 in Year 7, where rotation 3 (C-W-W-W) generated 29% higher wheat yields than rotations 1 and 2 (Table 5).

Across all sites in years 4 and 8, the average yield and annual NRs of wheat were significantly influenced by the preceding crops (Table 5). At Swift1, the wheat yields and NRs of rotations 10 (P-M-L-W) and 11 (P-P-P-W) in year 4, and rotation 4 in year 8 were higher than those of continuous wheat (Table 5). At this site, wheat generally performed better when preceded by field pea and lentil. At Swift2, the highest average yield and annual NR of wheat for rotation 11 in year 4 and rotation 3 in year 8 were observed when field pea and wheat were the respective preceding crops. However, yield and NR of wheat in rotation 11 in year 4 and in rotation 5 in year 8 were not statistically different from the average yield and annual NR of wheat in rotations 4, 10, 11, 12 (L-L-L-W), and 14 (L-C-P-W) in year 4, and most rotations in year 8 (Table 5). This follows the studies reported by Khakbazan et al. (2009) and Liu et al. (2020) which showed that field pea rotated with wheat increased the yields and economic return of wheat crop, in addition to other agronomic benefits.

Overall, pulse residues resulted in higher wheat yields and NRs than wheat residues (Table 5). The effect of pulse

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residues on wheat yields and NRs was significant in year 4 at all sites, but the effect was not as evident in year 8, compared to wheat residues in continuous wheat, or in rotations 2 and 3. Precipitation was low in year 8 of the study. The yield limiting factor was water shortage rather than N deficiency. Therefore, the N benefits from pulse crops did not materialize, considering the water-nutrient interaction.

### 3.4 Cereal with pulse rotation ranking: the SERF approach

The stochastic efficiency with respect to a function (SERF) at each site is presented in Fig. 3. This SERF approach has been previously described in detail (Khakbazan et al. 2017b, 2018, 2020). Absolute risk aversion coefficient (ARAC) ranged

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**Table 5** Residual effect of preceding crops on yield and net revenue of wheat for two 4-year rotation cycles at the Swift Current site 1 (Swift1) and site 2 (Swift2), Saskatchewan and Brooks, Alberta, Canada.

| Crop rotation | Crop yield (kg ha\(^{-1}\)) | Net revenue ($ yr\(^{-1}\) ha\(^{-1}\)) |
|---------------|----------------|----------------|
|               | Yr 2 | Yr 3 | Yr 4 | Yr 6 | Yr 7 | Yr 8 | Yr 2 | Yr 3 | Yr 4 | Yr 6 | Yr 7 | Yr 8 |
| Swift1        |      |      |      |      |      |      |      |      |      |      |      |      |
| 1: W-W-W-W    | 2189 b | 2034 a | 1914 c | 1995 a | 3248 b | 2160 b | 236 b | 192 a | 240 c | 252 a | 32 b | 163 b |
| 2: P-W-W-W    | 2884 a | 2096 a | 2322 bc | 2400 a | 3563 b | 2091 b | 100 a | 179 b | 178 bc | 168 a | 27 b | 178 b |
| 3: C-W-W-W    | 3234 a | 2227 a | 2335 abc | 2228 a | 4048 b | 2150 b | 31 a | 154 a | 158 abc | 204 a | 202 a | 166 b |
| 4: P-P-W-W    | 2920 a | 2652 ab | 2581 a | 2651 a | 93 a | 96 ab | 131 a | 62 a |
| 5: P-W-L-W    | 2943 a | 2520 abc | 2444 a | 2403 ab | 88 a | 121 abc | 159 a | 113 ab |
| 6: L-W-C-W    | 2879 a | 2189 bc | 2167 a | 2218 ab | 101 a | 186 bc | 216 a | 151 ab |
| 7: L-W-L-W    | 2849 a | 2685 ab | 2183 a | 2474 ab | 107 a | 89 ab | 213 a | 98 ab |
| 8: C-C-W-W    | 2821 a | 2333 abc | 2254 a | 2329 ab | 112 a | 158 abc | 198 a | 128 ab |
| 9: P-M-C-W    | 2569 abc | 2357 ab | 112 abc | 123 ab |
| 10: P-M-L-W   | 2905 a | 2515 ab | 46 a | 90 ab |
| 11: P-P-P-W   | 3002 a | 2459 ab | 27 a | 101 ab |
| 12: L-L-L-W   | 2507 abc | 2225 ab | 124 abc | 150 ab |
| 13: C-C-C-W   | 2393 abc | 2311 ab | 146 abc | 132 ab |
| 14: L-C-P-W   | 2782 ab | 2401 ab | 70 ab | 113 ab |

| Swift2        |      |      |      |      |      |      |      |      |      |      |      |      |
| 1: W-W-W-W    | 2054 b | 2200 a | 2456 dbc | 2260 a | 1347 a | 3174 a | 187 b | 281 a | 292 abc | 382 a | 23 a |
| 2: P-W-W-W    | 2398 a | 2475 a | 2385 dc | 2265 a | 1161 a | 3087 ab | 119 a | 227 a | 102 dc | 391 a | 5 ab |
| 3: C-W-W-W    | 2299 a | 2443 a | 2367 dc | 2166 a | 1338 a | 3249 a | 139 a | 233 a | 106 dc | 384 a | 38 a |
| 4: P-W-P-W    | 2310 a | 2901 abc | 2301 a | 2665 abc | 136 a | 1 ab | 284 a | 87 ab |
| 5: P-W-L-W    | 2346 a | 2645 abc | 2322 a | 2714 ab | 129 a | 52 abc | 279 a | 73 ab |
| 6: L-W-C-W    | 2473 a | 2377 dc | 2501 a | 2648 abc | 104 a | 104 dc | 242 a | 86 ab |
| 7: L-W-L-W    | 2446 a | 2810 dbc | 2323 a | 2555 bc | 110 a | 19 abc | 279 a | 168 bc |
| 8: C-C-W-W    | 2374 a | 2366 d | 2138 a | 2548 ab | 124 a | 106 a | 318 a | 107 ab |
| 9: P-M-C-W    | 2690 dbc | 2695 abc | 47 abc | 77 ab |
| 10: P-M-L-W   | 2955 ab | 2070 c | 9 ab | 206 c |
| 11: P-P-P-W   | 3416 a | 2903 abc | 100 a | 34 abc |
| 12: L-L-L-W   | 2926 ab | 2631 abc | 4 ab | 90 abc |
| 13: C-C-C-W   | 2369 dc | 2662 abc | 106 d | 83 abc |
| 14: L-C-P-W   | 2900 ab | 2536 abc | 16 ab | 110 abc |

| Brooks        |      |      |      |      |      |      |      |      |      |      |      |      |
| 1: W-W-W-W    | 2527 a | 3698 a | 3138 abc | 3901 ab | 1646 a | 2220 a | 158 a | 60 a | 28 abc | 152 ab | 237 a | 145 a |
| 2: P-W-W-W    | 3166 a | 4133 a | 2745 ab | 4476 a | 1898 a | 2164 a | 33 a | 145 a | 49 abc | 265 a | 187 a | 157 a |
| 3: C-W-W-W    | 3188 a | 3454 a | 2739 abc | 3906 ab | 1953 a | 2084 a | 28 a | 12 a | 50 abc | 153 ab | 177 a | 172 a |
| 4: P-W-P-W    | 3090 a | 3356 ab | 4490 a | 2069 a | 48 a | 71 ab | 268 a | 175 a |
| 5: P-P-W-W    | 3382 a | 3529 a | 4332 ab | 2276 a | 9 a | 105 a | 237 ab | 135 a |
| 6: L-W-C-W    | 3328 a | 2673 bc | 3857 ab | 1977 a | 1 a | 63 bc | 144 ab | 193 a |
| 7: L-W-L-W    | 3175 a | 3152 abc | 4174 ab | 1879 a | 31 a | 31 ab | 206 ab | 212 a |
| 8: C-C-W-W    | 2987 a | 2461 c | 3384 b | 1848 a | 68 a | 105 c | 51 b | 219 a |
| 9: P-M-C-W    | 2706 bc | 2145 a | 57 bc | 160 a |
| 10: P-M-L-W   | 3101 abc | 2218 a | 21 abc | 146 a |
| 11: P-P-P-W   | 3455 ab | 2383 a | 90 ab | 114 a |
| 12: L-L-L-W   | 3517 a | 2250 a | 102 a | 140 a |
| 13: C-C-C-W   | 3419 ab | 2466 a | 83 ab | 97 a |
| 14: L-C-P-W   | 3167 abc | 2190 a | 34 abc | 151 a |

Note: W = wheat, C = chickpea, P = field pea, L = lentil, M = mustard. Crop sequence for the second 4-year cycle (years 5–8) is repeated on the first 4-year cycle except for rotation 13. Crop sequence for rotation 13 is C-C-C-W for the first cycle and C-M-C-W for the second cycle. In the first year of study, all crops were seeded on wheat stubble seedbeds across three sites. A difference in means of crop yield and net revenue followed by the same lower letter for each site and each year is not statistically significant (P > 0.05)
from 0 to an upper bound of 0.006, with a risk neutral producer being defined by the value of ARAC=0, meaning that producers become more risk averse as the ARAC value increases.

When the certainty equivalent (CE) values of each rotation were ranked from highest to lowest, the ranking of rotation alternatives were different for each site. At Swift2, the most preferred rotation was rotation 12 (L-L-L-W) when the ARAC value was between 0 and 0.0049. Rotation 5 (P-W-L-W) became the preferred rotation at ARAC > 0.0049; however, at Swift1 and Brooks, as producers become more risk averse, they prefer more diversified crop rotations such as rotations 10 (P-M-L-W) and 14 (L-C-P-W) (Fig. 3). Since the CE is a measure of a certain payoff that a producer would have to receive to be indifferent to two alternatives, a producer at Swift1 with an ARAC value equal to 0.002, for example, is required to be paid about $60 ha\(^{-1}\) to become indifferent to rotation 10 and rotation 12.

Among the treatments at Swift1, rotations 10 and 12 reported a higher CE for a risk neutral producer, indicating that they were the most preferred treatments, with Rotation 12 being slightly preferred over rotation 10, while rotation 10 becomes the more preferred rotation when producers become more risk averse (ARAC > 0.00026). Rotation 12 included higher frequencies of lentil and yielded NRs that were much more volatile than the NRs of rotations without lentil. Two main sources of high variation of NR in rotation 12 were yields and prices of lentil. Lentil had the highest CV for yields (Table 4) and higher CV for prices than other crops (Table 1). These variabilities of yields and prices of lentil caused producers to prefer the more diversified rotation 10 over rotation 12, as they become more risk averse. All rotations were observed to have a higher CE over all levels of ARAC compared with the control, except for Rotation 13 (C-C-C-W-M-C-W) (Fig. 3a). Overall, at Swift1, as producers become more risk averse, they prefer rotations 10, 5 (P-W-L-W), 7 (L-W-L-W), 9 (P-M-C-W), and 14 over rotation 12 because these rotations include multiple crops that reduce the risk in their cropping decisions.

At Swift2, rotation 12 had the highest CE and was the most preferred treatment up to an ARAC value of 0.0049, while at higher ARAC values rotation 5 became the most risk preferred rotation. At Swift2 over two 4-year cycles, the CE of rotation 5 was among the lowest. As with Swift1, all rotations at Swift2 had a higher CE over all levels of ARAC compared to the continuous wheat rotation (Fig. 3b).

At Brooks, for risk neutral and slightly risk averse producers, rotation 12 had the highest CE, suggesting that rotation 12 is the most preferred treatment. However, as producers

![Crop rotation risk comparisons at Swift1, Swift2 and Brooks](image)

**Fig. 3** Certainty equivalent for different rotations in two 4-year rotation cycles (8 years) relative to rotation 1 (W-W-W-W) at the Swift Current site 1 (Swift1) and site 2 (Swift2), Saskatchewan and Brooks, Alberta, Canada. W wheat, C chickpea, P field pea, L lentil, M mustard. Crop sequence for the second 4-year cycle (years 5–8) is repeated on the first 4-year cycle, except for rotation 13. Crop sequence for rotation 13 is C-C-C-W for the first cycle and C-M-C-W for the second cycle.
become more risk averse (ARAC values greater than 0.0005), rotation 14 become the most risk preferred rotation. This is similar to Swift1, rotation 12, which included higher frequencies of lentil and revealed higher variabilities of crop yields and prices. These variabilities of yields and prices of lentil discouraged producers from selecting rotation 12, as they become more risk averse. All rotations had a higher CE over all levels of ARAC, compared to the baseline rotation 1 (W-W-W-W), except rotations 11 (P-P-P-W) and 8 (C-W-C-W) at ARAC values greater than 0.00245 (Fig. 3c).

Overall, for rotations 1–14 at the three sites, the results showed that risk averse producers were most likely to select rotation 10 at Swift1, rotations 12 and 5 at Swift2, and rotation 14 at Brooks, as these rotations provided a larger CE (Fig. 3). Risk neutral or slightly risk averse farmers may prefer rotation 12; however, more risk averse farmers prefer crop rotations with a higher degree of diversity, such as rotations 10, 14, or 5. These results from the two 4-year rotation cycles could provide producers with more solid information and confident recommendations in rotation decisions than those previously reported for the first 4-year cycle only (Khakbazan et al. 2020).

4 Conclusions

Long-term studies with comprehensive datasets are rare, here two cycles of fourteen, 4-year rotation systems (crop sequence from years 1 to 4 was repeated in years 5 to 8) at three sites, allowed for a first time comprehensive evaluation of the effects of crop rotation on the annual economic returns and risks of the entire rotations. Pulse, oilseed, and cereal crops in rotations included spring and durum wheat (W), field pea (P), chickpea (C), lentil (L), and mustard (M), with a continuous wheat rotation as the control. Results from an enterprise analysis showed that rotations with either high frequencies of lentil or diverse cropping generated significantly greater net revenues (NRs) than wheat monoculture systems. More diversified systems, such as rotation 10 (P-M-L-W) at Swift1, rotation 7 (L-W-L-W) at Swift2, and rotation 14 (L-C-P-W) at Brooks, provided statistically similar NRs to the high lentil frequency rotation 12 (L-L-L-W). However, caution needs to be taken regarding the fact that a high frequency of pulses could cause pest outbreaks and systems failure under specific circumstances. Risk analysis suggested that risk averse producers in Western Canada may select the more diversified rotations, including Rotation 10 at Swift1, rotation 12 and then rotation 5 (P-W-L-W) at Swift2, and rotation 14 at Brooks in order to reduce production risk and improve profitability, as these rotations provided larger certainty equivalents (CEs) than any other rotations, whereas risk neutral or slightly risk averse farmers could consider rotation 12 the preferred rotation choice as preceding pulses in a rotation provide positive agronomic and economic impacts on the following non-pulse crops and the entire system.

The demand for pulses has been increasing domestically and internationally because of the shift in diets to heathier plant-based food. People in North America are consuming pulse-focused food products like hummus more than ever. To meet the demand, Canada has expanded pulse production areas, which have benefited not only from increased domestic consumption but also from the generally rising growth in volume exports. This study uncovers new findings, such as the fact that adopting diverse crop rotations which include pulses, can significantly increase farm profitability while reducing the risks associated with rising production costs at the farm level, which may further motivate farmers to increase plantings of pulses such as lentils, peas, and chickpeas. Studies show that N fertilizer and fuel in traditional grain production systems are made up of 80% of the total energy inputs, while our study showed that adding pulses to crop rotations can reduce N fertilizer requirement by 38%. However, there is a negative impact of increased pesticide use in pulses, but in terms of carbon footprint as compared to N fertilizer, this is negligible. Additionally, pulse crops provide several other benefits, such as, improving soil fertility, increasing soil water and nutrient availability, and stimulating beneficial microbial activities in the soil environment. All of these previously listed benefits offer sustainable merits for agricultural systems.

Author Contribution Y. G., M. B., and K. L. conceptualized the research design, project administration, and data collection. M. K. developed methodology for economic analysis. M. K. and J. H. conducted formal analysis and investigation with inputs from all authors for processing of the data. M. K. and J. H. wrote the manuscript. All authors contributed to the revision of the manuscript. M. K. and Y. G. finalized the manuscript.

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Data availability The datasets during and/or analyzed during the current study are available from the corresponding authors on reasonable request.

Code availability Not applicable.

Declarations

Ethical approval The study was performed in accordance with the ethical standards as outlined by AAFC ethical standard protocols.

Consent to participate Not applicable.
Consent for publication  Not applicable.

Conflict of interest  The authors declare no competing interests.

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References

Agriculture and Agri-Food Canada. (2021) Canada: Outlook for Principal Field Crops, 2021-05-20. Government of Canada. https://agriculture.canada.ca/en/canadas-agriculture-sectors/crops/reports-and-statistics-data-canadian-principal-field-crops/canada-outlook-principal-field-crops-2021-05-20. Accessed 21 December 2021

Bainard LD, Navarro-Borrell A, Hamel C, Braun K, Hanson K, Gan Y (2017) Increasing the frequency of pulses in crop rotations reduces soil fungal diversity and increases the proportion of fungal pathogens in a semiarid agroecosystem. Agric Ecosyst Environ 240:206–214. https://doi.org/10.1016/j.agee.2017.02.020

Banniza S, Armstrong-Cho CL, Gan Y, Chongo G (2011) Evaluation of fungicide efficacy and application frequency for the control of Ascochyta blight in chickpea. Can J Plant Pathol 33:135–149. https://doi.org/10.1080/07060661.2011.561875

Bezdicek DF, Granstein D (1989) Crop rotation efficiencies and biological diversity in farming systems. Am J Altern Agric 4:111–119. https://doi.org/10.1080/0898189390002927

Burgess MH, Miller PR, Jones CA (2012) Pulse crops improve energy intensity and productivity of cereal production in Montana, USA. J Surv Eng-Asce 138:669–718. https://doi.org/10.1061/(ASCE)1044-0046.0000230

Chai Q, Nemecek T, Liang C, Zhao C, Yu A, Coulter JA, Wang Y, Hu F, Wang L, Siddique KHM, Gan Y (2021) Integrated farming with intercropping increases food production while reducing environmental footprint. P Natl Acad Sci USA 118:e2106382118. https://doi.org/10.1073/pnas.2106382118

Cox HW, Kelly RM, Strong WM (2010) Pulse crops in rotation with cereals can be a profitable alternative to nitrogen fertilizer in central Queensland. Crop Pasture Sci 61:752–762. https://doi.org/10.1071/CP09352

Entz MH, Baron VS, Carr PM, Meyer DW, Smith SR Jr, McCaughhey WP (2002) Potential of forages to diversify cropping systems in the Northern Great Plains. Agron J 94:240–250. https://doi.org/10.2134/agronj2002.0240

Eviews Quantitative Software. (2019). Retrieved from http://www.eviews.com/. Accessed 21 December 2021

Gan Y, Liang C, Hamel C, Cutforth H, Wang H (2011a) Strategies for reducing the carbon footprint of field crops for semiarid areas. A review. Agron Sustain Dev 31(4):643–656. https://doi.org/10.1007/s13593-011-0011-7

Gan Y, Liang C, Wang X, McConkey B (2011b) Lowering carbon footprint of durum wheat by diversifying cropping systems. Field Crop Res 122:199–206. https://doi.org/10.1016/j.fcr.2011.03.020

Gan Y, Liang C, Chai Q, Lemke RL, Campbell CA, Zentner RP (2014) Improving farming practices reduces the carbon footprint of spring wheat production. Nat Commun 5:1–13. https://doi.org/10.1038/ncomms6012

Gan Y, Hamel C, O’Donovan JT, Cutforth H, Zentner RP, Campbell CA, Niu Y, Poppy L (2015) Diversifying crop rotations with pulses enhances system productivity. Sci Rep UK 5:14625. https://doi.org/10.1038/srep14625

Ganeshamurthy AN (2009) Soil changes following long-term cultivation of pulses. J Agric Sci 147:699–706. https://doi.org/10.1017/S0021859609990104

Gustafson D, Yildiz F (2017) Greenhouse gas emissions and irrigation water use in the production of pulse crops in the United States. Cogent Food Agric 3:1334750. https://doi.org/10.1080/23311932.2017.1334750

Hamel C, Gan Y, Sokolski S, Bainard LD (2018) High frequency cropping of pulses modifies soil nitrogen level and the rhizosphere bacterial microbiome in 4-year rotation systems of the semiarid prairie. Appl Soil Ecol 126:47–56. https://doi.org/10.1016/j.apsoll.2018.01.003

Hardaker JB, Lien G (2010) Stochastic efficiency analysis with risk aversion bounds: a comment. Aust J Agr Resour Ec 54:379–383. https://doi.org/10.1111/j.1467-8489.2010.00498.x

Hardaker JB, Richardson JW, Lien G, Schummann KD (2004) Stochastic efficiency analysis with risk aversion bounds: a simplified approach. Aust J Agric Res 48:253–270. https://doi.org/10.1071/1467-8489.2004.00239.x

Hossain Z, Wang X, Hamel C, Knight JD, Morrison MJ, Gan Y (2016) Biological nitrogen fixation by pulses on semi-arid Canadian prairies. Can J Plant Sci 97:119–131. https://doi.org/10.1139/cjps-2016-0185

Kelley KW, Long JH Jr, Todd TC (2003) Long-term crop rotations affect soybean yield, seed weight, and soil chemical properties. Field Crop Res 83:41–50. https://doi.org/10.1016/S0378-4290(03)00055-8

Khakbazan M, Mohr RM, Derksen DA, Monreal MA, Grant CA, Zentner RP, Moulin AP, McLaren DL, Irvine RB, Nagy CN (2009) Effects of alternative management practices on the economics, energy and GHG emissions of a 4-year cropping system of the semi-arid prairies. Agron J 101:30–38. https://doi.org/10.1016/j.ajst.2008.11.005

Khakbazan M, Grant CA, Huang J, Smith EG, O’Donovan JT, Blackshaw R, Harker KN, Lafond GP, Johnson EN, Gan Y, May WE, Turkington TK, Lupwayi NZ (2014) Economic effects of preceding crops and nitrogen application on canola and subsequent barley. Agron J 106:2055–2066. https://doi.org/10.2134/agronj14.0253

Khakbazan M, Grant CA, Huang J, Zhong C, Smith EG, O’Donovan JT, Mohr RM, Blackshaw RE, Harker KN, Lafond GP, Johnson EN, May WE, Turkington TK, Gan Y, Lupwayi NZ, St Luce M (2017a) Economic impact of residual nitrogen and preceding crops on wheat and canola. Agron J 110:339–348. https://doi.org/10.2134/agronj2017.08.0489

Khakbazan M, Larney FJ, Huang J, Mohr RM, Pearson DC, Blackshaw RE (2017b) Economics of conventional and conservation practices for irrigated dry bean rotations in southern Alberta. Agron J 109:576–587. https://doi.org/10.2134/agronj2016.08.0480

Khakbazan M, Mohr RM, Huang J, Campbell E, Volkmar KM, Tomasiewicz DJ, Moulin AP, Derksen DA, Irvine BR, McLaren DL, Nelson A (2018) Economic and risk effects of rotation based on a 14-year irrigated potato production study in Manitoba. Am J Potato Res 95:258–271. https://doi.org/10.2135/ajpotr2017.02.017

Khakbazan M, Gan Y, Bandara M, Jianzhong H (2020) Economics of pulse crop frequency and sequence in a wheat-based rotation. Agron J 112:2058–2080. https://doi.org/10.1002/agj2.20182

Kirby EA (1981) Plant growth in relation to nitrogen supply. Ecol Bull 33:249–267
Pulse-included diverse crop rotations improved the systems economic profitability: evidenced in two 4-year...

Krupinsky JM, Tanaka DL, Merrill SD, Liebig MA, Hanson JD (2006) Crop sequence effects of 10 crops in the northern Great Plains. Agric Syst 88:227–254. https://doi.org/10.1016/j.agsy.2005.03.011

Lafond GP, May WE, Holzapfel CB, Lemke RL, Lupwayi NZ (2011) Intensification of field pea production: impact on agronomic performance. Agron J 103:396–403. https://doi.org/10.2134/agronj2010.0309

Li J, Huang L, Zhang J, Coulter JA, Li L, Gan Y (2019) Diversifying crop rotation improves system robustness. Agron Sustain Dev 39:38 https://hal.archives-ouvertes.fr/hal-02883280

Liu C, Cutforth H, Chai Q, Gan Y (2016) Farming tactics to reduce the carbon footprint of crop cultivation in semi-arid areas. A review. Agron Sustain Dev 36:1–16. https://doi.org/10.1007/s13593-016-0404-8

Liu K, Bandara M, Hamel C, Knight JD, Gan Y (2020) Intensifying crop rotations with pulse crops enhances system productivity and soil organic carbon in semi-arid environments. Field Crop Res 248:107657. https://doi.org/10.1016/j.fcr.2019.107657

Liu C, Plaza-Bonilla D, Coulter JA, Kutcher HR, Beckie HJ, Wang L, Gan Y (2022) Chapter Six - Diversifying crop rotations enhances agroecosystem services and resilience. In: Sparks DL (ed) Advances in Agronomy, vol 173. Academic Press, pp 299–335

MacWilliam S, Wismer M, Kulshreshtha S (2014) Life cycle and economic assessment of western Canadian pulse systems: the inclusion of pulses in crop rotations. Agric Syst 123:43–107. https://doi.org/10.1016/j.agsy.2013.08.009

MacWilliam S, Parker D, Marinangeli CPF, Trémorin D (2018) A meta-analysis approach to examining the greenhouse gas implications of including dry peas (Pisum sativum L.) and lentils (Lens culinaris M.) in crop rotations in western Canada. Agric Syst 156:101–110. https://doi.org/10.1016/j.agsy.2018.09.006

Manitoba Agriculture (2019) Cost of Production. Government of Manitoba. https://www.gov.mb.ca/agriculture/farm-management/production-economics/cost-of-production.html. Accessed 21 December 2021

Moussart A, Even MN, Lesnè A, Tivoli B (2013) Successive legumes tested in a greenhouse crop rotation experiment modify the inoculum potential of soils naturally infested by Aphanomyces euteiches. Plant Pathol 62:545–551. https://doi.org/10.1111/j.1365-3059.2012.02679.x

O’Donovan JT, Grant CA, Blackshaw RE, Harker KN, Johnson EN, Gan Y, Lafond GP, May WE, Turkington TK, Lupwayi NZ, Stevenson FC, McLaren DL, Khakbazan M, Smith EG (2014) Rotational effects of legumes and non-legumes on hybrid canola and malting barley. Agron J 106:1921–1932. https://doi.org/10.2134/agronj2014.0236

Pikula D, Rutkowski A (2014) Effect of leguminous crop and fertilization on soil organic carbon in 30-years field experiment. Plant Soil Environ 60:507–511. https://doi.org/10.17221/436/2014-PSE

Pratt JW (1964) Risk aversion in the small and in the large. Econometrica 32:122–136

Richardson JW, Klose SL, Gray AW (2000) An applied procedure for estimating and simulating multivariate empirical (MVE) probability distributions in farm-level risk assessment and policy analysis. J Agric Appl Econ 32:299–315. https://doi.org/10.1017/S10740780002037X

Richardson JW, Schumann K, Feldman P (2004) Simetar®: Simulation for Excel to Analyze Risk. Agricultural and Food Policy Centre, Department of Agricultural Economics, Texas A&M University, College Station

Richardson JW, Schumann K, Feldman P (2008) Simetar®: Simulation and Econometrics to Analyze Risk. Simetar, Inc., College Station

SAS Institute Inc (2014a) S. I. SAS® 9.3 Base SAS, 2nd edn. SAS Institute, Cary

SAS Institute Inc (2014b) S. I. SAS/STAT® 13.2 User’s Guide. SAS Institute, Cary

Saskatchewan Agriculture (2010-2019). Saskatchewan agriculture crop planning guide – Brown Soil Zones Government of Saskatchewan. https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/crop-guides-and-publications/guide-to-crop-protection. Accessed 21 December 2021

Saskatchewan Agriculture. (2018-2019) Farm Machinery Custom and Rental Rate Guide. Government of Saskatchewan. 2018. http://www.publications.gov.sk.ca/details.cfm?ID=76527. Accessed 21 December 2021

St Luce M, Grant CA, Zeharbi BJ, Ziadi N, O’Donovan JT, Blackshaw RE, Harker KN, Johnson EN, Gan Y, Lafond GP, May WE, Khakbazan M, Smith EG (2015) Legumes can reduce economic optimum nitrogen rates and increase yields in a wheat–canola cropping sequence in western Canada. Field Crop Res 179:12–25. https://doi.org/10.1016/j.fcr.2015.04.003

St. Luce M, Lemke R, Gan Y, McConkey B, May W, Campbell C (2020) Diversifying cropping systems enhances productivity, stability, and nitrogen use efficiency. Agron J 112:1517–1536. https://doi.org/10.1002/agj2.20162

Zentner RP, Campbell CA, Biederbeck VO, Miller PR, Selles F, Fernandez MR (2001) In search of a sustainable cropping system for the semi-arid Canadian prairies. J Surv Eng Asce 18:117–136. https://doi.org/10.1061/(ASCE)0733-9410(2001)127:2(117)

Zentner RP, Wall DD, Nagy CN, Smith EG, Young DL, Miller PR, Campbell CA, McConkey BG, Brandt SA, Lafond GP, Johnston AM, Derksen DA (2002) Economics of crop diversification and soil tillage opportunities in the Canadian prairies. Agron J 94:216–230. https://doi.org/10.2134/agronj2002.0216

Zentner RP, Lafond GP, Derksen DA, Nagy CN, Wall DD, May WE (2004) Effects of tillage method and crop rotation on non-renewable energy use efficiency for a thin Black Chernozem in the Canadian Prairies. Soil Tillage Res 77:125–136. https://doi.org/10.1016/j.still.2003.11.002

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