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# *Soil residual water and nutrients explain about 30% of the rotational effect in 4-year pulse-intensified rotation systems*

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## Abstract

Diverse crop rotations enable the best use of residual soil water and nutrients, thus, decreasing production inputs. Here, we determined the effect of cropping sequences on soil residual water and nutrients, and the performance of subsequent wheat (*Triticum aestivum* L.). Nine rotation systems were evaluated at Swift Current, Saskatchewan, and Brooks, Alberta, from 2010 to 2014. Pea (P) (*Pisum sativum* L.) and lentil (L) (*Lens culinaris* Medik.) as preceding crops before wheat (W) or the rotation systems with pea (PPPW) or lentil (LLLW) included more than once in the 4-yr rotations had the highest residual soil water and N in the 30-90 cm depths, and continuous wheat (WWWW) had the lowest. Preceding pea and lentil increased the grain yield of the subsequent wheat by 26% and 18%, respectively, as compared with the continuous wheat. Variance partitioning of redundancy analysis revealed that soil residual water and residual N explained 12.4 to 42.7% (average 30%) of the yield variation observed in the subsequent wheat, with the rest of the rotational benefits unexplainable by soil residual water and residual nutrients. Investigation of the factors other than soil water and nutrients that contribute to the succeeding wheat yield may further enhance the rotational effect.

**Keywords:** Rotational effect, pulses, rhizobacteria, symbiosis, soil water, N mineralization, C:N ratio

It has been projected that about 60% more food will be required to meet the global demand by 2050 (FAO and DWFI 2015). However, achieving the production goal is often constrained by low availability of water and poor soil nutrients (Rasouli et al. 2014), and the challenge is severe in arid and semi-arid regions like western Canada (Borontov et al. 2005; Gan et al. 2015; Hou et al. 2012). Many cropping approaches have been developed to tackle these challenges. For example, cereal-summerfallow rotation is used to minimize the risk of crop failure due to moisture deficits (Sun et al. 2013; Tanaka and Aase 1987); minimum- or zero-tillage is practiced in the areas with high risk of wind and soil erosion (Hansen et al. 2015; Nyakudya and Stroosnijder 2015); continuous cropping is used to sequester more carbon to the soil and increase soil organic matter (Bailey et al. 2001; Pedersen 1992); and speciality crops are included in crop rotations to diversify conventional monoculture cropping (Gan et al. 2015) .

On the semiarid Canadian prairie, one of the greatest changes in cropping system in the past two decades is the inclusion of annual pulses, such as chickpea (*Cicer arietinum* L.), dry pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.). Including pulses in crop rotations is shown to increase soil available N (Peoples et al. 1995), improve soil water conservation in the deeper soil layers (Gan et al. 2011; Wang et al. 2012), and enhance overall soil health (Lupwayi and Kennedy 2007). More importantly, the inclusion of pulses lowers the carbon footprints of the crop production (Gan et al. 2014), improves overall farming sustainability (O'Dea et al. 2015; Zentner et al. 2007), and enhances agro-ecosystem productivity (Gan et al. 2015). Similar results have been reported in other regions of the world (Andrews and Carroll 2001; Galantini et al. 2000). In the Mediterranean, the use of pulses to enhance soil N has been practiced for decades, and the advantages have been widely demonstrated (Christiansen et al. 2015). In northwestern India, pulse residues are used for improving the N economy and soil fertility in cereal-based cropping system (Sharma and Behera 2008).

With the benefits of pulse crops, there is a tendency to increase the frequency of pulses in rotation in western Canada. However, there is a lack of information on how the change in pulse crop frequency and sequences in rotation impacts soil water and nutrient availability and the system productivity. The objective of this study was to quantify the effect of crop sequences in rotation and immediately-preceding crops on soil residual water and nutrients, and the agronomic performance of the subsequent wheat in different 4-yr crop rotation patterns. We hypothesize that a higher frequency of pulses in rotation increases residual soil water and nutrients, which provides greater benefits to the succeeding wheat compared with a wheat monoculture system.

## MATERIAL AND METHODS

### *Experimental design*

Field experiments were conducted at the Agriculture and Agri-Food Canada Research Centre, in Swift Current, Saskatchewan (50°25´N, 107°44´W) and the Crop Diversification Centre South (CDCS), in Brooks, Alberta (50°33´N, 111°53´W). The soil at the Swift Current site was a Swinton Silt Loam (Orthic Brown Chernozem in the Canadian soil classification) with saturated paste pH of 6.5 in the 0-15 cm depth, and a silt loam texture with 31.4% sand, 50.4% silt and 18.2% clay. The soil at the CDCS site was an Orthic Brown Chernozen (Chin Soil Series) with sandy loam soil texture containing 46% sand, 32% silt and 22% clay and saturated paste pH was 7.8 in the 0-15 cm depth.

The 4-yr crop sequence cycle study was completed as three separate trials at the two sites. The 1st cycle was initiated in 2010 and completed in 2013 at Swift Current, the 2nd cycle was started in 2011 and completed in 2014 at Swift Current, and the 3rd cycle was initiated in 2011 and completed in 2014 at Brooks. Each cycle included nine crop rotation treatments (Table 1). Hard red spring wheat (cv. AC Lillian) was grown at each site prior to the start of the trials using best crop management practices for wheat production in the local area (Campbell et al. 2011). At harvest, 15-cm height of wheat stubble was retained in the field, and the rest of the plant residue was chopped and spread evenly across the plots. In Year-1 of the crop sequence, all crops (wheat and pulses) were planted between the rows of wheat stubble from the previous year. The crops were arranged using a randomized complete block design with four replicates. In Year 2 and Year 3, pulse crop and wheat was planted following the specifics of the experiment design (Table 1) and crop residue remained on the field. In Year 4 of the crop sequence, spring wheat was uniformly planted in each of the Year-3 plots.

### *Planting and plot management*

All plots were planted using a no-till plot seeder (modified Noble Hoe drill frame with 8 Morris "C" shanks supporting Atom Jet side band openers at 25-cm row spacing) that was equipped with fertilizer, inoculant and seed boxes, allowing for the application of fertilizers, seed and

*Rhizobium* inoculants for pulses in a one-pass operation without pre-planting tillage. The plot size was 4 × 12 m at Swift Current and 3 × 12 m at Brooks. Seeding was completed in the first to second week of May. The seed rates were determined on the basis of pre-seeding germination, estimated field emergence rate, and seed weight, to target an optimal plant density for each crop (Table 2).

For the Year-1 pulse crops, pre-packaged seeds and granular *Rhizobium* inoculants were evenly distributed in the seed rows. The Year-1 wheat was fertilized with urea ($CH_4N_2O$ containing 46% of N) at the soil test recommended rates (Table 2). All plots were fertilized with monoammonium phosphate ($NH_4H_2PO_4$ containing 11% of N and 51% of $P_2O_5$), side-banded to 30 mm distance from the seed-rows and 70 mm deep, to provide a 22 kg ha$^{-1}$ of actual P (soil P + fertilizer P). No additional N-fertilizer was applied to the pulse crops. Wheat and pulse seeds were treated with Vitaflo 280 and Apron Maxx, respectively, using the label rates. Glyphosate was used for pre-seeding weed 'burn-off' treatment each year and an additional post-harvest glyphosate treatment was used when necessary. No hand-weeding was used in any year since weed infestation (spectra and intensity) was considered the part of rotational effects.

### *Data collection*

Soil samples were collected within 3 days prior to seeding and again within 3 days after crop harvest each year. Two 30-mm diameter soil cores were taken to the depth of 120 cm in each plot. Each of the two cores was divided into 0-15, 15-30, 30-60, 60-90, and 90-120 cm increments. Soil samples were analyzed for soil nutrient and water content using standard procedures adopted at the Agriculture and Agri-Food Canada Research Centre Soil Chemistry Service Laboratory (Gan et al. 2007; Zentner et al. 2004). Total soil nitrogen was determined using the Kjeldahl nitrogen digestion method, and the soil water content was measured using gravimetric method. The measured values were converted to volumetric units using soil bulk densities of 1.16, 1.29, 1.39, 1.54 and 1.63 g cm$^{-3}$ in Swift current, and 1.22, 1.30, 1.40, 1.50, and 1.60 g cm$^{-3}$ in Brooks, respectively, for the five soil depths (Gan et al. 2015; Zentner et al. 2004).

At full maturity, the center six-plant rows in each plot were harvested with a plot combine for the determination of grain yield. The plants in a 1.0 m$^2$ area in each plot were hand-harvested for the determination of the biomass of grain and straw. Plant density (number of plants $m^{-2}$) and days to maturity were recorded. Weather data was obtained from a weather station located on the Research Farm, about 500 meters from the plot site (Table 3).

Rainwater use efficiency (RUE) was calculated as:

RUE = wheat yield / precipitation

where, wheat yield is the grain yield (kg $ha^{-1}$); precipitation represents the cumulative value (mm) during the crop growing season (1 May to 31 August).

### *Statistical analysis*

Data were analyzed using the MIXED procedure of SAS (Littell et al. 2006), and the analysis was conducted in two steps. First, the effect of immediately-previous crops on wheat was analyzed, and followed by the analysis of the effect of the 4-yr rotation sequence on wheat performance. For the previous crop effect, those rotations with the same previous crop were pooled together. The wheat (W) in the treatments WWWW, PWWW and CWWW was all preceded by a wheat crop; the wheat in the treatments PWPW and PPPW was preceded by a pea (P) crop; the wheat in the treatments LWLW and LLLW was preceded by lentil (L), and wheat in the CWCW and CCCW was preceded by a chickpea (C) crop. In the analysis of rotation effect, all crops in the 4-yr sequence were taken into account. Rotation sequences or previous crops were considered fixed factor, and replicates and site-year (environsites) were considered random factors. The normal distribution and the homoscedasticity of variance of the model residuals were checked using Shapiro-Wilk and Bartlett test. In cases where no significant interaction between rotation sequences or previous crop and environsites was shown, data from all environsites were pooled together. In cases where there was a significant interaction between rotation sequence or previous crop and environsites, the data were analyzed for each environsite separately. For determination of the effect of rotation sequence on soil traits, soil from the different depths was considered as a repeated measure. Least significant difference test was used to separate treatment means for significance at a 5% level of probability.

Redundancy analysis (RDA) was used to identify the factors that most strongly influenced agronomic performance of wheat (i.e., yield, total mature biomass, mature biomass harvest index, mature biomass seed weight, 1000 seed weight, days to maturity, plants $m^{-2}$, and rainwater use efficiency). The function *ordistep* (forward selection) was used to select a set of nonredundant predictors of the agronomic performance of wheat among the explanatory variables, which included soil water, soil nitrogen, and soil phosphorus, along with rotation sequence or previous crop. The relative influence of these predictors on the agronomic performance of wheat was quantified using the *varpart* function in *vegan* (R version 3.2) that is an RDA-based variance partitioning method.

## RESULTS

### *Soil water and nutrients*

Spring soil water contents differed among the environsites (Fig. 1). At the Swift Current 2013 (Fig. 1a, 1d) and Brooks 2014 (Fig. 1c, 1f) soil water contents were the lowest in the upper soil layers (0-15 cm and 15-30 cm) and increased with soil depth. In contrast, soil water content at Swift Current 2014 (Fig. 1b, 1e) was highest in the 0-15 cm soil layer and decreased with soil depth. Comparing across the previous crop treatments, Swift Current 2013 (Fig. 1a) and 2014 (Fig. 1b) both had significantly different soil water contents in the 0-15 cm and the 60-90 cm soil layer, but this effect was only observed in the 60-90 cm soil layer for the rotations (Fig. 1d, 1e). . Plots with wheat as the previous crop had the highest soil water content in the top soil layer, and plots with field pea and lentil previous crops and intensified field pea (PPPW) and intensified lentil (LLLW) rotations had the highest soil water contents in the 60-90 cm layer. Previous pea crops and intensified pea rotations had the highest soil water contents in the 15-30 cm and 30-60 cm soil layers along with the continuous chickpea.

Total soil N at the spring seeding time exhibited different depth patterns among the environsites (Fig. 2). There was no strong shift in total soil N among the various soil depths at Swift Current 2013 (Fig. 2a), whereas N content decreased with soil depth at Swift Current 2014 (Fig. 2b), and increased with soil depth at Brooks 2014 (Fig. 2c). The effects of previous crops and rotation sequences on total soil N were similar at the Swift Current 2013 and Swift Current 2014 sites, where the strongest effects were observed in the 30-60 cm and 60-90 cm soil depths (Table 4). Pea and lentil as the previous crops and intensified pea or lentil rotations (PPPW and LLLW) had the highest total N content at these soil depths and wheat as the previous crop or wheat monoculture (WWWW, PWWW, CWWW) had the lowest total soil N. Similar trends of the treatment effect on soil N were observed at Brooks as those at the two Swift Current sites. However, at Brooks, wheat previous crops and the wheat monoculture rotation had the lowest total N in the upper soil depths (0-15 cm and 15-30 cm), whereas the pulse crops and pulse-intensified rotations had significantly higher soil N content.  Unlike soil N, total soil phosphorus did not differ significantly among the previous crop treatments or the different rotation sequences at any soil depth at any of the sites (Table 4).

### ***Agronomic performance of wheat***

The agronomic performance of wheat was strongly affected by the previous crop and rotational sequence (Table 5). Wheat yield was highest in plots preceded by pea and lentil, which had a 26% and 18% increase in yield, respectively, over plots preceded by wheat (Fig. 3). Similarly, pea (PWPW and PPPW) and lentil (LWLW and LLLW) intensified rotations had a significantly greater yield over continuous wheat rotations or rotations that included one pulse crop (PWWW and CWWW). The PPPW rotation produced the highest wheat yield, which was a 32% increase over continuous wheat. The inclusion of chickpea in the rotations had no significant effect ($P > 0.05$) on the grain yield of wheat. Similar effects were observed for water use efficiency and 1000-seed weight as pea and lentil intensified rotations and previous crops had significantly higher rainwater use efficiency (Fig. 3) and 1000-seed weight compared to continuous wheat or rotations with one pulse crop.

Total biomass at full maturity was significantly great in wheat preceded by pea crops compared to all other previous crops, and had a 21% increase over continuous wheat (Fig. 3). No significant difference in total biomass was observed for wheat preceded by lentil and chickpea as previous crops compared to continuous wheat. The only rotation that had a significantly higher total mature biomass compared to continuous wheat was three continuous years of pea (PPPW), which was 31% higher. However, harvest index of wheat was highest in wheat preceded by lentil, and there was no significant difference among the other preceding crops. Three continuous years of lentil (LLLW) was the only rotation that had a higher harvest index compared to continuous wheat.

Plots preceded by wheat and rotations with continuous wheat or one pulse every four years (PWWW and CWWW) had the longest number of days (97-98) to mature for wheat in the final year of the rotation (Fig. 3). Wheat in the rotations with two or more chickpeas, CWCW and CCCW, matured earliest (94 and 95 days, respectively), followed by wheat preceded by lentil (LWLW = 95 d, LLLW = 96 d, and then pea (PWPW = 97 d, PPPW = 96 d).

### *Soil properties and crop sequences on wheat agronomic performance*

Using redundancy analysis (RDA), we were able to identify the set of non-redundant factors that influenced the agronomic performance of wheat at each environsite. At all environsites, soil water and total soil N were important factors that influenced the agronomic performance of wheat. Total soil N was an important factor related to yield, rain water use efficiency, total biomass at maturity, and 1000-seed weight for the Swift Current 2013 and 2014 environsites. In the Brooks 2014 environsite, soil water and total soil N (15-30 cm) were factors that influenced the yield and total biomass. Variance partitioning revealed the relative influence of the soil properties and previous crop or rotation sequences on the agronomic performance of wheat. The soil properties (soil water and total soil N) explained 27.5, 24.0 and 10.6% of the variation in Brooks 2014, Swift Current 2014, and Swift Current 2015, respectively (Fig. 4). Rotation sequence explained more of the variance in agronomic performance of wheat compared to previous crop for Swift Current 2013 (35.5% vs. 25.0%) and Brooks 2014 (23.1% vs. 12.4%), but explained equally for Swift Current 2014 (37.2% vs. 37.3%). The rotation sequences or previous crop interacted with the soil properties, which is shown by the overlap in the Venn diagrams (Fig. 4). The remaining proportion of the variation related to the soil properties may be explained by spatial variation of these properties in the environsites.

## DISCUSSION

Water shortage is a key factor affecting sustainable crop production in the rainfed, semiarid regions of the Canadian prairies. The amount of water stored in the soil profile plays an important role in seed germination, seedling establishment and the early stages of plant growth (Gan et al. 2009). However, the amount of water remaining in the 0-120 cm soil profile at crop harvest can be above the 'permanent wilting point' of water content for the semiarid prairie soil (Kröbel et al. 2014). Short growing season may constrain some crops from having adequate time to utilize all of the plant available water during the growing period, and some water is unused by crop plants and left in the soil profile (Gan et al. 2015). The amount of water remaining in the soil profile by the following spring may be related to many factors. Precipitation during the previous growing season is one of the main factors. For example, Swift Current in 2012 received 248 mm of precipitations during the crop-growing season, leading to 198 mm of water in the 0-120 cm soil profile at the 2013 spring planting time, whereas the Swift Current 2013 growing season had 198 mm of precipitation and the following spring (2014) had only 111 mm of water detected in the 0-120 cm soil profile. Also, other factors may affect spring soil water availability, such as the amount of snowfall during the fall-winter period (Kormos et al. 2014), stubble retention at the harvest of the previous crops that affects the catchment of snow (Hu et al. 2015), spring soil temperature , and soil organic matter that affects water drainage (Hayes et al. 2008), water holding capacity (Naeth et al. 1991) and snowmelt runoff (Rhoton et al. 2002).

Soil water distribution in the profile reflects the ability of crop plants to utilize the available water from various depths. In the present study, we measured the detailed water use profile at the various rooting depths. We found higher water content in the lower soil layers (60-90 cm) in plots preceded by pea and lentil and the rotation with intensified pea (PPPW) or lentil (LLLW). Most soil water use occurred in the top soil layer in pulse intensified rotation because pea and lentil are shallow-rooted crops with approximately 77- 85% of their roots located in the 0 to 40 cm soil depth (Liu et al. 2010). This allows pulse plants to use water mainly from the top 60 cm soil layer, leaving water in the deeper soil layers (below 60 cm) for use by deeper-rooted crops (e.g. wheat) that are grown the following year (Liu et al. 2011a; Wang et al. 2012). The water use profile by pulse crops had little or no change with soil water availability or total water consumption by the crops. For example, soil water available at the spring planting was 111, 198, and 296 mm, respectively, at Swift Current in 2014, Swift Current in 2013, and Brooks in 2014, but this did not affect the water use profile in the 0-120 cm depth by the pulse crops. Likewise, total amount of water consumption was 182, 255, and 264 mm at those three environsites, which did not affect the water use profile by the pulse crops.

Agricultural production is increasingly dependent on the amount and distribution of precipitation, particularly in water-limited environments (Turner 2004). All phases of plant development are influenced by rainfall during the crop growing period (De Jong et al. 2008), which plays a more important role in crop yield than pre-planting residual soil water (Gan et al. 2007). Averaged cross these environsites, rainwater productivity of wheat preceded by pea crop averaged 16.1 kg ha$^{-1}$ mm$^{-1}$, and lentil at 15.1; they were 22 % greater than the wheat preceded by wheat (12.8 kg ha$^{-1}$ mm$^{-1}$ (Fig. 3). Similarly, pea (PWPW and PPPW) or lentil (LWLW and LLLW) intensified rotation systems had 22% greater rainwater use efficiency compared to continuous wheat (WWWW) or rotations that included one pulse crop before wheat (PWWW or CWWW). The higher rainfall use efficiency associated with pea and lentil intensified rotations may be due to the development of 'biopores' in the soil that allow easier root penetration of water by the subsequent cereal (Cresswell and Kirkegaard 1995; Liu et al. 2011b; Turner 2004).

In the present study, soil residual N at the planting of the Year-4 wheat was 52, 68 and 110% higher in the soil with pulse crops (pea, lentil and chickpea) compared with wheat crops in Swift Current 2013, Swift Current 2014, and Brooks 2014, respectively. The magnitude of the soil N increases after pulses were greater compared to those reported by other researchers. For example, O'Dea et al. (2015) found that pulse crops increased the long-term, no-till agroecosystem resilience and sustainability by increasing the available N supply (26-50%) compared to wheat systems in Montana. Other studies in Saskatchewan showed that the average available soil N in the 0-120 cm soil profile was 76.3 kg ha$^{-1}$ in the fields following pulses, which was 57.5% greater compared to fields following cereal crops in a 3-year pulse-cereal crop rotation trial over five study cycles (Gan et al. 2015). Mineralization of soil organic matter releases available N to the soil that provides benefits to the subsequent crops (Campbell et al. 2008; Gan et al. 2015); this process help reduce the amount of inorganic N-fertilizer required in farming systems (Koutika et al. 2004; Ross et al. 2015). Also, the plant–*rhizobial* associations in pulse crop roots are known to be an effective $N_2$-fixing system in which atmospheric $N_2$ is transformed into ammonia to provide a large portion of the N requirements for plant growth (Jensen et al. 2012). The fixed-N in the crop residues, roots and nodules have higher N contents and lower C:N ratios than cereal crops, and pulse residues are more likely to result in net mineralization and a build-up of inorganic N in soil (Jensen et al. 2012; Kumar and Goh 1999). Concentrations of inorganic N in field soils are generally higher following a pulse than a cereal crop (Peoples et al. 2001). The higher concentration of pulse residues added to the soil in pulse intensified rotations could accelerate the soil organic matter decomposition rate due to the lower C:N ratio (Nave et al. 2009).

It has been widely recognized that pulses offer a large benefit of soil N to the subsequent crop (Gan et al. 2010; Walley et al. 2007) and the benefit of soil water in the arid and semiarid areas (Angadi et al. 2008; Cutforth et al. 2013; Wang et al. 2012). However, previous studies do not determine whether or not these benefits can be recognized in a longer-term rotation or the benefits can be enhanced by using pulse-intensified rotation systems. In the present study, we quantified the relative contribution of residual soil water and nitrogen, along with the effect of previous crops and the rotation sequences on the performance of subsequent wheat. Analysis showed that residual soil water and nitrogen, albeit of substantially importance, only explained 27.5% (Brooks 2014), 24% (Swift Current 2014), and 10.6% (Swift Current 2013) of the variation of the grain yield of wheat grown the subsequent year. The magnitude of the rotational effects differed among the environsites. The Brooks 2014 had the greatest rotational benefits among the three environsites. We have no explanation about the different magnitude of rotational effect among sites. It might be possible that the sandy-loam soil at Brooks had greater microbial activities due to higher soil temperature that accelerated the decomposition of pulse straw that enhanced nutrient availability compared with Swift Current. It is well known that higher soil temperature increases crop straw decomposition and nutrient release (Yin et al. 2016). Also, it might be possible that the Brooks soil had a more diversified microbial community than the Swift Current soil, as more diversified soil microbial community enhances soil nutrient supply and promote root growth of wheat crop the following year (Borrell et al. 2016; St. Luce et al. 2016; Yang et al. 2013). More detailed analysis is required to elucidate this effect.

At the present study, we found that the pulse-intensified rotation enhanced the rotational benefits further, but at a small scale with most of the benefits occurred in wheat crop grown immediately after a pulse. The rest of the yield increase in wheat following a pulse or the wheat crop grown in a pulse-intensified rotation was unexplainable. Besides residual soil water and N, the cumulative crop rotational effect over years may be due to additional factors, such as improved soil microbial properties (Ellouze et al. 2013; Lupwayi et al. 2015), suppression to pathogens (Bazghaleh et al. 2016; Cruz et al. 2012; Esmaeili Taheri et al. 2016), and enhanced biological processes and the feedback to the root growth of the following crops (St. Luce et al. 2016; Yang et al. 2012). For example, biotic processes in the soil can be affected by pulse rhizosphere exudates that decompose crop residues (Lupwayi and Kennedy 2007; Yang et al. 2013). Additionally, some abiotic factors, such as choice of plant hosts (Bazghaleh et al. 2016), weed infestation (Harker et al. 2005), root maggot (Dosdall et al. 2012), may have had some effects. Future research in determining rotational effect may need to pay more attention on these aspects.

## CONCLUSION

An increased demand for plant-based protein, favorable market for pulse crops, and the widely recognized rotational benefits that pulse crops offer have stimulated the continuous increase of the areas seeded to pulse crops on the Canadian prairie. Information on the residual soil water and soil N following a pulse crop and the effect on the performance of the subsequent wheat in the rotation is limited for the semiarid areas. This study was designed uniquely to address those issues. Our analysis showed that the increased soil N and water availability after pulse crops were important factors that explain less than 30% of the increased yield of the subsequent wheat and the rest of the rotational benefits were unexplainable by soil water and available N. Research on the other aspects of rotational effect such as soil microbial community and pest infestation may provide further insight of the large rotational effect with pulses.

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## Figure caption

Figure 1. Effect of the previous crop (a-c) and 4-year rotation sequence (d-f) on total soil water content at the different soil depths at wheat sowing, measured at Swift Current 2013 (a,d), Swift Current 2014 (b,e), and Brooks 2014 (c,f). *, significant differences at $P < 0.05$, ** at $P < 0.01$, and *** at $P < 0.001$.

Figure 2. Effect of the previous crop (a-c) and 4-year rotation sequences (d-f) on total soil nitrogen at the different soil depths at wheat sowing, measured at Swift Current 2013 (a, d), Swift Current 2014 (b, e), and Brooks 2014 (c, f). *, significant differences at $P < 0.05$, ** at $P < 0.01$, and *** at $P < 0.001$.

Figure 3. Effect of the previous crop (a-d) and 4-year rotations (e-h) on wheat yield, total mature biomass, rainwater use efficiency, and days to maturity. Bars are means of samples from four replicates and three different locations ($n$=12); bars not followed by the same letter are significantly different according to the LSD test ($P < 0.05$).

Figure 4. Variance components explaining the variation in wheat productivity. Percentage values followed by $^{***}$ are significant at $P < 0.001$.

Table 1. Crop frequencies and sequences used in 4-year rotation systems.

| Pre-test | Rotation code | Yr-1 | Yr-2 | Yr-3 | Yr-4 | Note |
|---|---|---|---|---|---|---|
| Wheat | WWWW | Wheat | Wheat | Wheat | Wheat | Continuous wheat crop as a conventional cereal monoculture system |
| Wheat | PWWW | Field Pea | Wheat | Wheat | Wheat | 1 shallow-rooting pulse in every 4 yrs, with pea as the main pulse crop |
| Wheat | CWWW | Chickpea | Wheat | Wheat | Wheat | 1 deep-rooting pulse in every 4 yrs, comparing with the previous shallow-rooting pea effect |
| Wheat | CWCW | Chickpea | Wheat | Chickpea | Wheat | 2 pulses every 4 yrs, only deep-rooting chickpea alternated with a wheat break |
| Wheat | CCCW | Chickpea | Chickpea | Chickpea | Wheat | Chickpea-intensified in rotation |
| Wheat | LWLW | Lentil | Wheat | Lentil | Wheat | 2 pulses every 4 yrs, with shallow-rooting lentil alternated with a wheat break |
| Wheat | LLLW | Lentil | Lentil | Lentil | Wheat | Lentil-intensified in rotation |
| Wheat | PWPW | Field pea | Wheat | Field pea | Wheat | 2 shallow-rooting pulses in every 4 yrs, alternated with a wheat break |
| Wheat | PPPW | Field pea | Field pea | Field pea | Wheat | Pea-intensified in rotation |

Table 2. Crop variety, seeding rate and fertilizer applied in 4-year crop rotation systems.

| Site | Crop | Cultivar | Seeding rate (seeds $m^{-2}$) | Fertilizer ( N-P-K, kg $ha^{-1}$) | |
|---|---|---|---|---|---|
| | | | | Yr-1 | Yr-2, 3, 4 |
| Swift Current | Spr. wheat | AC Lillian | 250 | 80-17-0 | 55-22-0 |
| | Chickpea | CDC Frontier | 50 | 4-17-0 | 5-22-0 |
| | Field pea | CDC Meadow Yellow | 90 | 4-17-0 | 5-22-0 |
| | Lentil | CDC Maxim CL Red | 140 | 4-17-0 | 5-22-0 |
| Brooks | Spr. wheat | AC Lillian | 250 | 80-17-0 | 54-20-0 |
| | Chickpea | CDC Frontier | 50 | 4-17-0 | 4-20-0 |
| | Field pea | CDC Meadow Yellow | 90 | 4-17-0 | 4-20-0 |
| | Lentil | CDC Maxim CL Red | 140 | 4-17-0 | 4-20-0 |

Table 3. Monthly precipitation during the crop growing season in Swift Current, Saskatchewan and Brooks, Alberta.

| Month | Swift Current, Saskatchewan | | | | | | Brooks, Alberta | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | LTM | 2011 | 2012 | 2013 | 2014 | LTM |
| | mm | | | | | | | | | | |
| May | 111.6 | 66.5 | 102.0 | 13.6 | 33.5 | 51.2 | 23.1 | 65.2 | 67.5 | 29.6 | 41.0 |
| June | 126.3 | 116.9 | 113.4 | 113.3 | 116.0 | 77.1 | 88.7 | 156.2 | 92.6 | 93.1 | 64.5 |
| July | 75.9 | 68.8 | 21.1 | 53.5 | 33.6 | 60.1 | 32.7 | 13.4 | 54.0 | 33.8 | 44.9 |
| August | 95.8 | 35.5 | 11.3 | 17.6 | 105.6 | 47.4 | 26.4 | 40.1 | 17.1 | 29.6 | 35.3 |
| Total | 410 | 288 | 248 | 198 | 289 | 236 | 171 | 275 | 231 | 186 | 186 |

LTM, the long-term means of 1981 to 2010 (data source: Environment and Climate Change Canada).

Table 4. Summary of ANOVA showing the significances of treatment effects on soil water, total soil nitrogen and total soil phosphorus at wheat planting time, at Swift Current 2013, Swift Current 2014, and Brooks 2014.

| | Previous Crop effect | | | Rotation sequence effect | | |
|---|---|---|---|---|---|---|
| | SC 2013 | SC 2014 | Brooks | SC 2013 | SC 2014 | Brooks |
| | | | ***P*-value** | | | |
| **Soil water** | | | | | | |
| 0-15 cm | **0.019** | **0.025** | 0.56 | 0.26 | 0.09 | 0.68 |
| 15-30 cm | 0.62 | 0.66 | **0.0009** | 0.81 | 0.62 | **0.0052** |
| 30-60 cm | 0.36 | 0.69 | **0.0197** | 0.49 | 0.62 | **0.0071** |
| 60-90 cm | **0.0023** | **0.011** | 0.81 | **0.033** | **0.041** | 0.97 |
| 90-120 cm | 0.32 | 0.25 | 0.22 | 0.17 | 0.23 | 0.36 |
| **Soil N** | | | | | | |
| 0-15 cm | 0.32 | **0.045** | **<0.0001** | 0.63 | 0.08 | **<0.0001** |
| 15-30 cm | 0.85 | **0.025** | **0.050** | 0.91 | 0.17 | **<0.0001** |
| 30-60 cm | **0.0046** | **0.0006** | 0.92 | **0.0020** | **0.0008** | 0.62 |
| 60-90 cm | **<0.0001** | **0.0032** | 0.11 | **<0.0001** | **0.044** | 0.17 |
| 90-120 cm | 0.19 | 0.39 | **0.037** | 0.12 | 0.45 | 0.10 |
| **Soil P** | | | | | | |
| 0-15 cm | 0.69 | 0.43 | 0.42 | 0.10 | 0.72 | 0.68 |
| 15-30 cm | 0.69 | 0.42 | 0.92 | 0.28 | 0.88 | 0.99 |
| 30-60 cm | 0.24 | 0.71 | 0.93 | 0.57 | 0.75 | 0.54 |
| 60-90 cm | **0.035** | 0.39 | 0.17 | 0.30 | 0.95 | 0.50 |
| 90-120 cm | 0.14 | 0.68 | 0.14 | 0.45 | 0.96 | 0.26 |

Table 5. Significance of the effect of previous crop and the rotation sequence on various agronomic variables in the field study

| | Previous crop effect | Rotation sequence effect |
|---|---|---|
| | *P*-value | |
| Yield | **<0.0001** | **<0.0001** |
| Total mature biomass | **0.0001** | **<0.0001** |
| Mature biomass harvest index | **0.0021** | **0.0257** |
| Mature biomass seed weight | **0.0001** | **0.0001** |
| 1000 seed weight | **<0.0001** | **<0.0001** |
| Days to maturity | **<0.0001** | **<0.0001** |
| Plants per $m^2$ | **0.0004** | **0.0029** |
| Rainwater use efficiency (RUE) | **<0.0001** | **0.0008** |

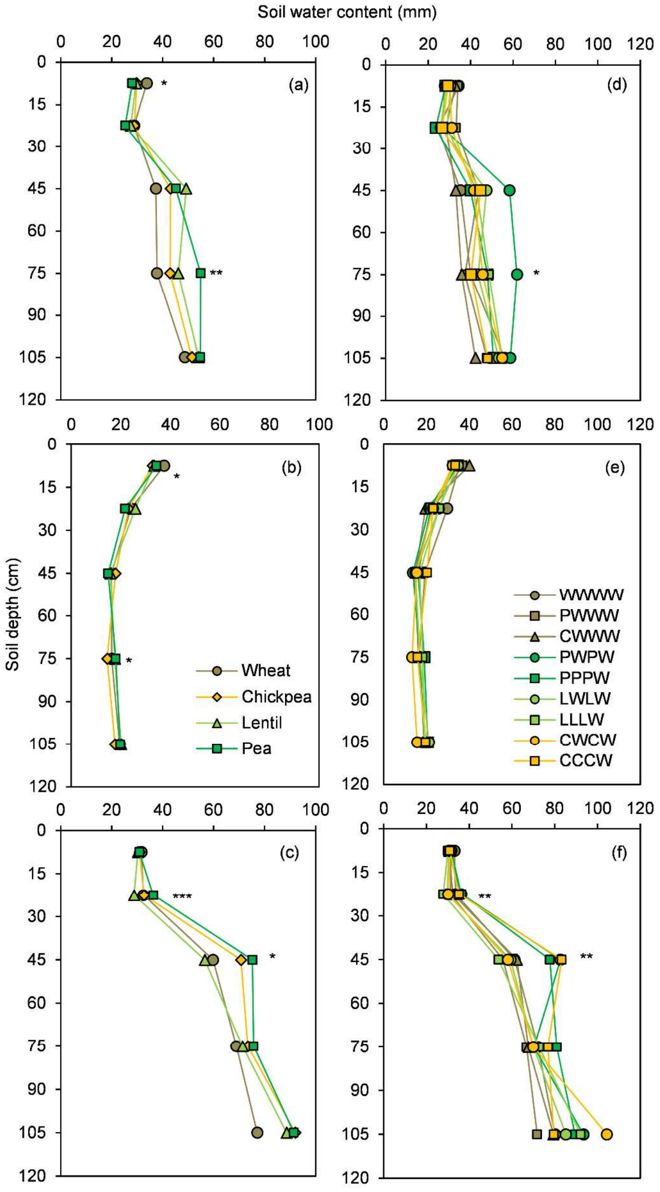

Fig. 1. Effect of the previous crop (a-c) and 4-year rotation sequence (d-f) on total soil water content at the different soil depths at wheat sowing, measured at Swift Current 2013 (a,d), Swift Current 2014 (b,e), and Brooks 2014 (c,f). *, significant differences at P < 0.05, ** at P < 0.01, and *** at P < 0.001.

700x1250mm (96 x 96 DPI)

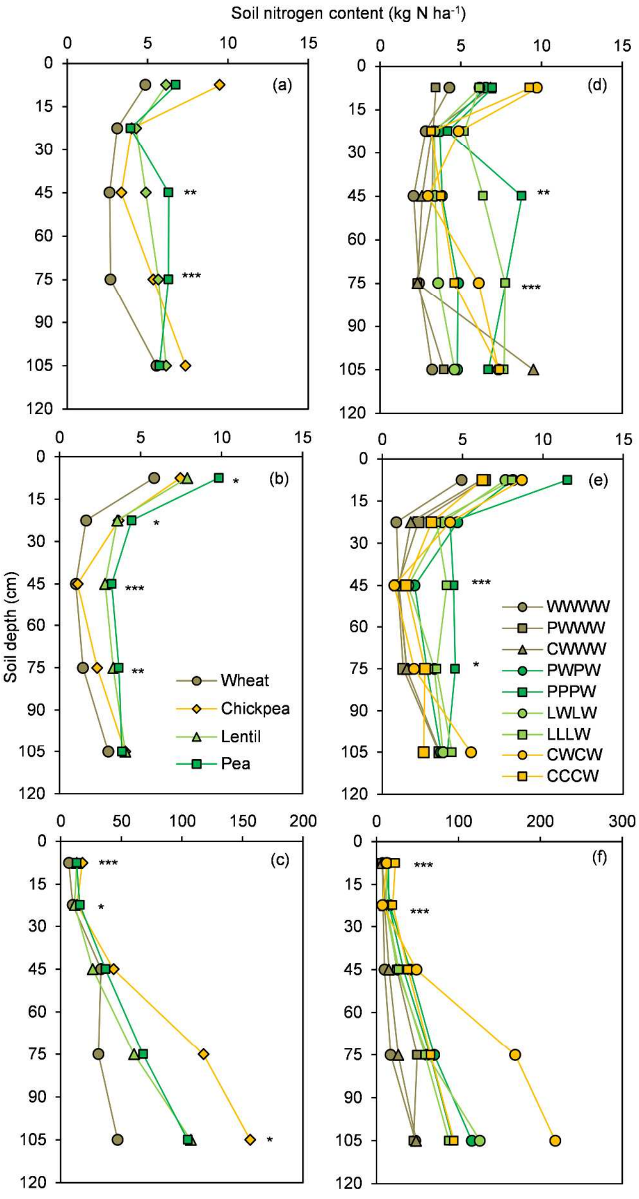

Fig. 2. Effect of the previous crop (a-c) and 4-year rotation sequences (d-f) on total soil nitrogen at the different soil depths at wheat sowing, measured at Swift Current 2013 (a, d), Swift Current 2014 (b, e), and Brooks 2014 (c, f). *, significant differences at P < 0.05, ** at P < 0.01, and *** at P < 0.001.

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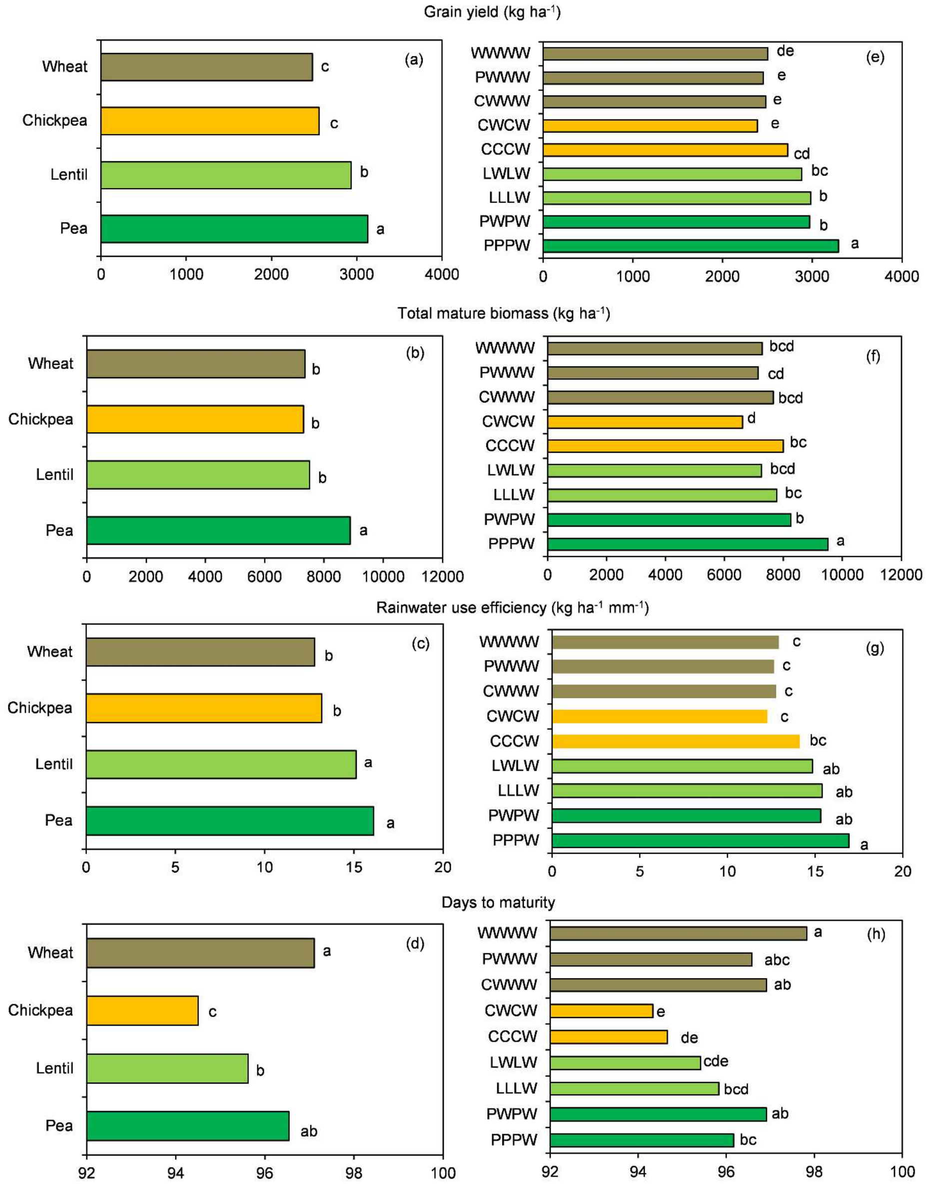

Fig. 3. Effect of the previous crop (a-d) and 4-year rotations (e-h) on wheat yield, total mature biomass, rainwater use efficiency, and days to maturity. Bars are means of samples from four replicates and three different locations (n=12); bars not followed by the same letter are significantly different according to the LSD test ($P < 0.05$).

1068x1352mm (96 x 96 DPI)

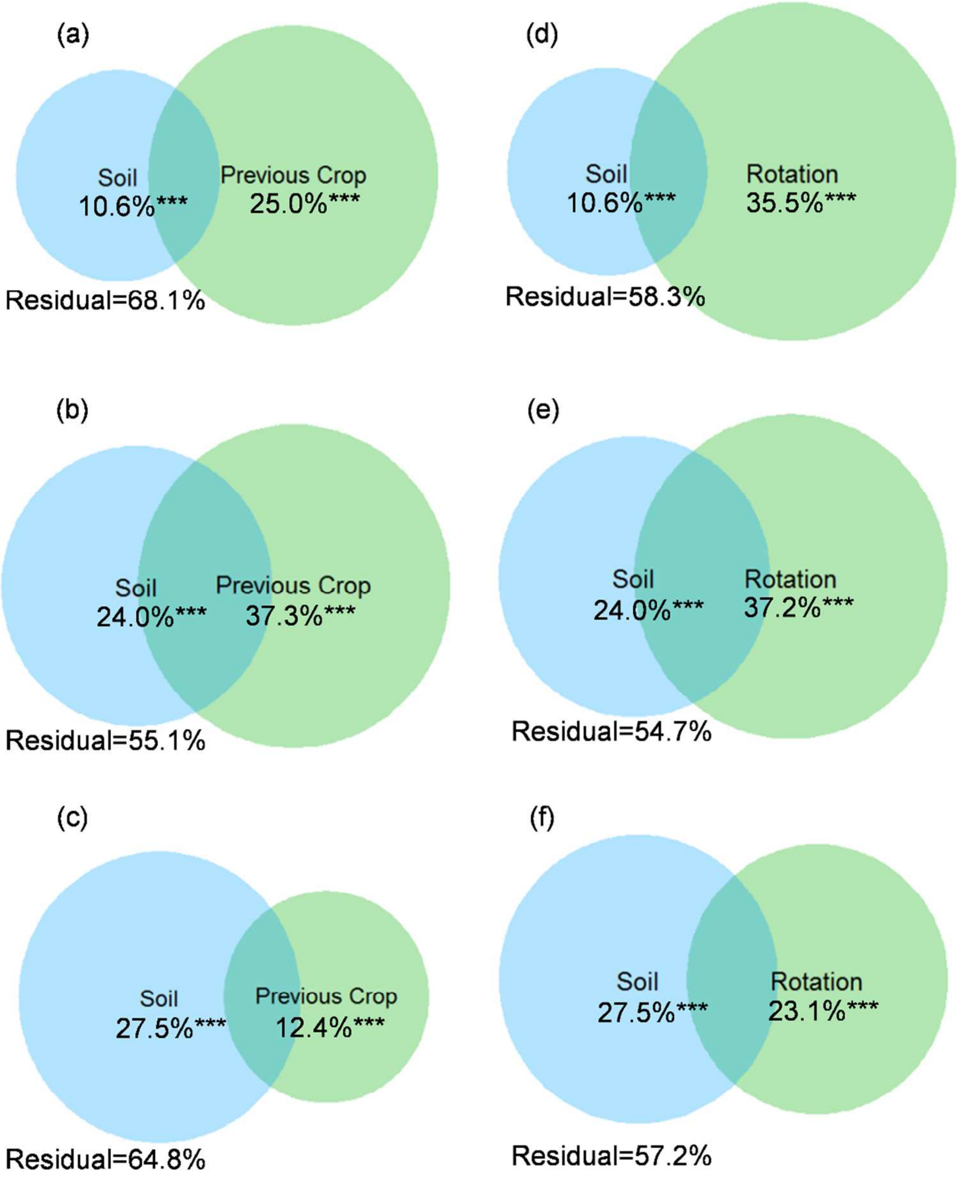

Fig. 4. Variance components explaining the variation in wheat productivity. Percentage values followed by *** are significant at P < 0.001.

318x384mm (96 x 96 DPI)