Long-term rotation impacts soil total macronutrient levels and wheat response to applied nitrogen, phosphorus, potassium, sulfur in a Luvisolic soil

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Abstract: Over the last 20–30 yr, increased intensification and diversity of crop rotations, along with increasingly higher yielding crop cultivars on the Northern Great Plains, has increased nutrient removal from cropping systems, but also increased crop residues returned to the soil, affecting soil nutrient cycling, soil carbon (C) and nutrient balances. The University of Alberta Breton Classical Plots, established in 1929, consist of two crop rotations of varying diversity and intensity: (1) wheat–fallow (WF); and (2) 5 yr, cereal–forage. Superimposed on these rotations are eight fertility treatments, including a check (control), manure, balanced (NPKS), and nutrient exclusion treatments. Soil total C, nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) levels were measured on soil samples (0–15 cm) collected from both rotations in 2013. Wheat yields and N uptake for the 2007–2018 growing seasons from both rotations were compared. In the 5 yr rotation, soil total C, N, and S, wheat yield and wheat N uptake were greater than the WF rotation. Soil total P levels were not different between the two rotations, but soil total K was higher in the WF rotation. Despite higher soil S and comparable soil P, wheat yield and N uptake response to applied P and S was greater in the 5 yr rotation compared with the WF rotation. Response to applied N in the 5 yr rotation was muted because of significant inputs of biologically fixed N. Wheat also responded to applied K in the 5 yr rotation. These results highlight the need to replace exported nutrients.

Key words: crop rotation, wheat, fertilizer response, soil nutrient balance, long-term, manure.

Résumé : Depuis 20 à 30 ans, l’intensification et la diversification des assolements, combinées à l’usage de cultivars au rendement toujours plus élevé dans le nord des grandes plaines, ont réduit la quantité d’oligoéléments que prélèvent les cultures tout en augmentant le volume de résidus végétaux restitué au sol, ce qui a modifié le cycle des oligoéléments, la concentration du C dans le sol et le bilan des éléments nutritifs. Les parcelles Breton, aménagées par l’Université de l’Alberta en 1929, consistent en deux assolements de diversité et d’intensité variables : (1) assolement blé–jachère (BJ) et (2) assolement céréales–fourrages de 5 ans. À ces assolements s’ajoutent huit plans de fertilisation, soit l’usage de fumier, l’application d’un engrais équilibré (NPKS) et des traitements qui excluent certains oligoéléments, en plus d’une parcelle témoin. La concentration totale de C, N, P, K et S a été établie au moyen d’échantillons prélevés sur les deux assolements, à une profondeur de 0 à 15 cm, en 2013. Les auteurs ont comparé le rendement du blé et l’absorption de N des deux assolements durant la période végétative de 2007 et de 2018. La concentration totale de C, de N et S dans le sol ainsi que le rendement du blé et l’absorption de N par la culture étaient plus élevés pour l’assolement de cinq ans que pour l’assolement BJ. La concentration totale de P dans le sol était similaire pour les deux, mais l’assolement BJ laisse plus de K dans le sol. Malgré un sol plus riche en S et une concentration comparable de P, l’application de P et de S augmente plus le rendement du blé et l’absorption du N sur l’assolement de 5 ans que sur l’assolement BJ. La réaction de l’assolement de 5 ans à l’application d’un engrais N est atténuée en raison du plus important volume d’intrants contenant du N fixé biologiquement. Le blé de l’assolement de 5 ans réagit aussi aux applications de K. Ces résultats soulignent qu’il faut remplacer les oligo-éléments exportés. [Traduit par la Rédaction]

Mots-clés : assolement, blé, réaction aux engrais, bilan des éléments nutritifs dans le sol, long terme, fumier.
Introduction

Over the last 20–30 yr, increased intensification and diversity of crop rotations, along with increasingly higher yielding crop cultivars on the Northern Great Plains, has increased nutrient removal from cropping systems, but it also increased crop residues returned to the soil, affecting soil nutrient cycling, soil carbon (C), and nutrient balances (Janzan et al. 1998; Grant et al. 2002; Schlegel et al. 2005; Lafond et al. 2012; Lemke et al. 2012a, 2012b). The results of long-term rotation experiments show that intensity and diversity are not only adjectives describing crop rotations but also potential management tools that can be implemented to optimize soil nutrient and biogeochemical cycles, and increase crop production in response to increasing global demand (Richter et al. 2007; Richter and Yaalon 2012).

The University of Alberta Breton Plots are home to long-term crop rotations of varying diversity and intensity. The Breton Classical Plots, consisting of a wheat–fallow, and 5 yr, cereal–forage rotation, were established in 1929 with the purpose of identifying suitable crop rotations for and nutrient deficiencies in the Luvisolic soils of Alberta (Bentley et al. 1971). As an agricultural soil, Luvisols proved less productive than their Chernozem counterparts because much of the organic matter in the surface leaf litter was lost during clearing of the forest, leaving the leached and poorly structured Ae mineral horizon for cultivation (Bentley et al. 1971; Pettapiece et al. 2010; Dyck et al. 2012). Currently, 42 944 km² of land in the Boreal Forest Natural Region of Alberta is under agricultural management (ABMI 2019), including Dark Gray Chernozemic, Dark Gray Luvisolic, and Gray Luvisolic soils. The area of potentially arable land in the Dark Gray and Gray Soil Zones of Alberta is approximately 88 000 km² (Bentley et al. 1971). Under changing climate, agricultural production on Luvisolic soils has the potential to increase significantly, and understanding how these soils respond to management will be critical if such an expansion occurs.

Early reports of results from the Classical Plots showed significant response of wheat, oats, and barley to applied nitrogen (N; calcium ammonium nitrate, diammonium phosphate, and ammonium sulfate), phosphorus (P; super-triple-phosphate), and manure, and also a strong response of clover to applied P (Wyatt 1931; McAllister 1934; Wyatt 1936). Newton (1936) first reported the Luvisolic soils at Breton to be deficient in sulfur (S) and reported a significant response of red clover to S applied in the previous season. Later, Wyatt (1945) also reported the response of alfalfa and clover to applied S. The effects of rotation on crop response to fertilizer were first emphasized in the publication by Wyatt et al. (1939) and later in Wyatt (1945) and Juma et al. (1997a), where it was reported that wheat response to added N and P was much greater following clover than following wheat or fallow. Later, S cycling and response of cereals and forages to applied S were investigated more extensively (Cormack et al. 1951; Renner et al. 1953; Bentley et al. 1955; Bentley et al. 1956; Bentley et al. 1960; Pawluk and Bentley 1964). Other investigations focussed on rotation effects on speciation and cycling of N (Khan 1971; Monreal and McGill 1985; Rutherford and Juma 1989; Wani et al. 1991, 1994; Juma 1995), P (Odynsky 1936; McKenzie et al. 1992; Morel et al. 1994), and C (Juma et al. 1997a, 1997b; Campbell et al. 1997; Janzen et al. 1998; Grant et al. 2001; Izaurralde et al. 2001a, 2001b; Paul et al. 2004; Izaurralde et al. 2006).

Examples of rotation and fertilization management effects on soil levels of all four macronutrients — N, P, potassium (K), and S — and crop response fertilizer N, P, K, and S are rare in the scientific literature. Consistent long-term rotation and nutrient management at the Breton Classical Plots provide a unique opportunity to investigate the effects of long-term rotation and fertilizer management on yields and nutrient balances as reflected in soil nutrient stocks. Therefore, the primary purpose of this work is to highlight the effects of long-term rotation and fertilizer management on soil total C and total macronutrient (N, P, K, and S) levels, wheat yield, and N uptake.

Materials and Methods

The Breton Plots research site is located approximately 100 km southwest of Edmonton, AB, near the town of Breton (53°07′N, 114°28′W). At the site, the long-term average (1967–2018) hydrological year (1 Oct.–30 Sept.) temperature, precipitation, growing season (1 Apr.–31 Aug.) precipitation, and growing degree days (base 5) are 3.1 °C, 558 mm, 370 mm, and 1111, respectively (Alberta Agriculture and Forestry 2019). The results presented in this work focus on the Breton Classical Plots experiment established in 1929 (Dyck et al. 2012). The Breton Classical Plots consist of eight fertility treatments super-imposed on two rotations. The two rotations are (1) a 2 yr wheat (Triticum aestivum L.)–fallow (WF) rotation and (2) a 5 yr wheat (Triticum aestivum L.)–oats (Avena sativa)–barley (Hordeum vulgare L.)–alfalfa (Medicago sativa)–brome (Bromus tectorum) hay (WOBHH) rotation. The alfalfa–brome hay is first established in the barley phase of the rotation. The eight fertility treatments (since 1980) are (1) check (control or no fertilizer), (2) manure, (3) NPKS, (4) NKS(–P), (5) lime, (6) NPK(–S), (7) PKS(–N), and (8) NPS(–K). For this paper, results from the lime treatment (5) will not be reported. The soil underlying the Classical Plots experiment is classified as an Orthic Gray Luvisol.

The rotation and fertility treatments are distributed over six series (A through F) and 11 plots (numbered 1 through 11), similar to an alpha–numeric grid. The series are oriented north–south with series A, B, C, D, and F hosting one of the five rotation phases of the WOBHH rotation in a given year as determined by the
rotation sequence, and lime is applied to the east half of these series to restore soil pH to 6.5 when soil pH (measured every 5 yr) falls below 6.0. Series E is split into east and west halves and the two phases of the WF rotation alternate between east and west halves—lime is applied to both halves to restore pH to 6.5 when soil pH falls below 6.0.

To compare the productivity and nutrient status of the two rotations, only the grain and straw yield and N uptake in grain, straw, and grain+straw of the wheat phase from the 2007–2018 growing seasons will be reported in this work. Over this period, the wheat varieties AC Barrie (2007) and CDC Go (2008–2018) were seeded at a rate of 100 kg ha$^{-1}$ in both rotations.

For the wheat phase of the WF rotation, in the appropriate treatments, fertilizer N, P, K, and S rates were 90, 22, 46, and 20 kg N, P, K, and S ha$^{-1}$ as urea, super-triple-phosphate, potash, and elemental S, respectively; composted cattle manure rate was targeted for an N application of 90 kg N ha$^{-1}$. For the wheat phase of the 5 yr rotation, fertilizer P, K, and S rates were the same as the WF rotation, but N was applied at 50 kg N ha$^{-1}$, and manure rate was targeted to achieve 87.5 kg N ha$^{-1}$. In both rotations, manure and fertilizer nutrients were broadcast and incorporated with a disc or rotary tiller in the spring prior to seeding, except for manure treatment in the WOBHH rotation when manure was applied in the previous fall during hay plough-down. For the other phases of the 5 yr rotation, P, K, and S rates were the same as for wheat, but N rates were 75, 50, and 0 kg N ha$^{-1}$ for oats, barley, and alfalfa–brome, respectively; and in the manure treatment, an additional manure application of 87.5 kg N ha$^{-1}$ was applied prior to barley planting.

In the fallow phase of the WF rotation, weeds were controlled with herbicide as needed. Weeds were controlled using herbicides in the wheat phase of the WF rotation and 5 yr rotation. Herbicide selection is based on an annual weed survey conducted following seeding. In the fall after the second year of the hay phase, glyphosate up is applied, followed by plough-down with a two-way disc.

Grain and straw yields were measured on hand-harvested samples from 1 m$^2$ areas at four locations in both east and west halves (only cropped half in WF rotation) of each plot in each series. A hand sickle was used to cut the harvest sample at ground level (grain and straw; placed in a cloth bag and dried at 60 °C in a forced-air oven for 4 d. Following drying, grain was separated from the straw using a stationary thresher. Grain and straw were weighed and scaled to yields as kg ha$^{-1}$. Subsamples of grain and straw from the 2007–2018 growing seasons were analyzed for total N at a commercial laboratory. Nitrogen uptake (kg N ha$^{-1}$) of grain and straw was estimated by multiplying the yield by percent total N (kg/kg) in the sample divided by 100. After collection of hand-harvest samples, a plot combine was used to remove the remaining grain. Residual straw was distributed evenly over each treatment plot area, but it should be noted that this practice only began in 2000.

In the fall of 2013, composite soil samples (from three locations) in the east and west halves of each plot in each series (all phases of both rotations) from 0 to 7.5 cm and 7.5 to 15 cm depths were collected using a Giddings, hydraulic soil coring rig (cylindrical soil cores, 3.55 cm i.d.). Soil samples in their entirety were air-dried and ground to pass through a 2 mm sieve, and the dry weight and total volume of each sample (estimated using soil core dimensions and number of cores in the composite sample) were used to estimate bulk density. Soil samples were submitted to the Natural Resources Analytical Laboratory in the Department of Renewable Resources at the University of Alberta and analyzed for total C and total N by combustion (AOAC 2000), and total S, total P, total K in nitric acid digests with inductively coupled plasma optical emission mass spectrometry (Thermo Fisher Scientific 2010). Total C and nutrient concentrations were converted to mass per hectare by multiplying concentrations by bulk density, the sample depth, and the appropriate unit conversion factor. These values from both depths were added to estimate levels in the 0–15 cm depth. Soil pH was measured on 5:1, deionized-water:soil extracts, and average pH in the 0–15 cm depth was estimated according to $-\log(10^{-pH(0-15)} + 10^{-pH(7.5-15)})/2$.

**Statistical analysis**

Because the Classical Plots were established in 1929, the dawn of statistical experimental design, the treatments are not randomized, and the rotations are not fully phased (replicated). For soil properties measured at only one time (2013), east and west plot halves were used as replicates. Because each plot is large, it was assumed that samples from different plot halves were far enough away from each other to be considered independent. To offset the lack of spatial replication, yield and N uptake over a period of 12 yr (replication in time) were used. Temporal autocorrelation for selected variables (annual precipitation, growing season precipitation, and grain yield of the east half of the NPKS treatment of the 5 yr rotation) was assessed by calculating the Pearson’s correlation coefficient as a function of temporal lag and was found to be negligible.

For soil properties (total C, N, P, K, S, and pH), a general linear model was fit separately to each soil property following optimized Box–Cox transformation in the MiniTab version 18 statistical software package. Factors for the general linear model were rotation (WF or WOBHH) and rotation nested within fertility treatment. Rotation and fertility treatment (rotation) means were compared with the Tukey’s method at 95% confidence. For yield and N uptake, a mixed model was fit to non-transformed data using the restricted maximum
likelihood method in the MiniTab version 18 statistical software package. For the mixed model, random factors were year and year \(\times\) rotation, whereas rotation and fertility treatment (rotation) were set as fixed factors. Rotation and fertility treatment (rotation) means were compared with the Tukey’s method at 95% confidence.

Results and Discussion

Growing season conditions

Annual temperature and precipitation, growing season precipitation and growing season growing degree days (GDD) for 2007–2018 are presented in Table 1. Over this period, the average annual and average growing season precipitation were 57 and 37 mm below the long-term average, respectively, whereas the average annual and average growing season temperature, and GDD were 0.4 °C, 0.1 °C, and 151 GDD above the long-term average, respectively. Over this 12 yr period, a wide range of growing conditions — cold and wet (e.g., 2011), cold and dry (e.g., 2014), warm and dry (e.g., 2015), warm and wet (e.g., 2016) — are represented, suggesting this 12 yr period is a representative sample of the long-term growing conditions affecting yields and N uptake.

Rotation average soil properties and yields

Rotation average soil total C, N, and S were significantly higher in the 5 yr rotation compared with the WF fallow rotation (Table 2). Both rotations had equal levels of soil total P, but the WF rotation had significantly higher levels of soil total K (Table 2). Rotation average grain yield, straw yield, grain N, straw and grain + straw N were all significantly higher in the 5 yr rotation (Table 3).

Given the fairly consistent rotations and fertilizer treatments since 1980, the soil total C and nutrient levels (Table 2) are likely a reflection of the long-term C and nutrient balances in these soils. Detailed information about all the components of the element balances is not available, but considering a simple balance equation where change in mass of each element is equivalent to the difference in element additions and losses, the following are likely reasonable explanations for the observed differences between the two rotations in Table 2.

Soil total C levels are higher in the 5 yr rotation compared with the WF rotation, because greater frequency of cropping, overall higher productivity, and the inclusion of deep-rooted forages in the 5 yr rotation have resulted in greater C additions to the soil, increasing total C levels. It should be noted that straw from the cereal crops returned to the plots starting only in 2000, so roots and stubble were the primary crop residues returned to the soil for 71 out of the 90 yr that the experiment has been running.

Soil total N levels are higher in the 5 yr rotation compared with the WF rotation, because of greater inputs of biologically fixed N from alfalfa in the hay phase of the rotation, resulting in greater net N additions and higher yields in subsequent crops, despite more frequent N losses from removal of grains and forage biomass in harvests. Over the 5 yr rotation cycle, in treatments receiving N fertilizers, the average annual N application rate was about 35 kg N ha\(^{-1}\) compared with an average annual rate of 45 kg N ha\(^{-1}\) in the WF rotation.

Soil total P levels are consistent across both rotations suggesting similar P balances. Over a rotation cycle,

| Year  | Precipitation (mm) | Average temp. (°C) | Growing season GDD |
|-------|-------------------|-------------------|-------------------|
|       | Annual\(^a\) | Growing season\(^b\) | Annual\(^a\) | Growing average\(^b\) | Growing season GDD\(^c\) |
| 2007  | 664 | 491 | 3.6 | 11.6 | 1249 |
| 2008  | 375 | 286 | 3.5 | 11.3 | 1279 |
| 2009  | 278 | 180 | 3.2 | 11.1 | 1278 |
| 2010  | 645 | 487 | 3.2 | 11.2 | 1121 |
| 2011  | 532 | 376 | 2.4 | 11.1 | 1251 |
| 2012  | 556 | 439 | 4.8 | 12.1 | 1382 |
| 2013  | 442 | 284 | 3.0 | 11.5 | 1378 |
| 2014  | 530 | 286 | 2.5 | 11.8 | 1297 |
| 2015  | 412 | 180 | 4.5 | 12.5 | 1315 |
| 2016  | 548 | 392 | 5.3 | 12.9 | 1216 |
| 2017  | 551 | 340 | 3.7 | 12.1 | 1152 |
| 2018  | 480 | 252 | 2.6 | 12.2 | 1228 |
| Long-term average | 500 | 333 | 3.5 | 11.8 | 1262 |
| Normal\(^d\) | 558 | 370 | 3.1 | 11.7 | 1111 |

\(^a\)1 Oct. of previous calendar year to 30 Sept. of stated calendar year.
\(^b\)1 Apr.–31 Aug. of stated calendar year.
\(^c\)Growing degree days, base 5 °C.
\(^d\)1961–2018 average.
average annual fertilizer P additions to relevant treatments are greater in the 5 yr rotation (22 kg P ha\(^{-1}\)) compared with the WF rotation (11 kg P ha\(^{-1}\)), but these were apparently offset by greater removals in the 5 yr rotation due to greater cropping frequency and diversity. Expected harvest P removals, calculated using average yields from the NPKS treatment from the Breton Classical Plots and typical nutrient concentrations for western Canada (Alberta Agriculture and Forestry 2020) were 12, 17, 12, and 17 kg P ha\(^{-1}\) for wheat (both WF and 5 yr), oats, barley, and hay (two cuts), respectively.

Soil total K levels are significantly lower in the 5 yr rotation compared with the WF rotation likely because of greater harvest K losses from all phases but especially the high-yielding forage phases of the 5 yr rotation. Over a rotation cycle, average annual fertilizer K rates in the relevant treatments was 46 kg K ha\(^{-1}\) compared with 23 kg K ha\(^{-1}\) in the WF rotation but are offset by much greater, annual harvest losses due to greater cropping frequency and diversity. Expected harvest K removals, calculated using average yields from the NPKS treatment from the Breton Classical Plots and typical nutrient concentrations for western Canada (Alberta Agriculture and Forestry 2020) were 15, 21, 17, and 137 kg K ha\(^{-1}\) for wheat (both WF and 5 yr), oats, barley, and hay (two cuts), respectively.

Soil total S levels are higher in the 5 yr rotation compared with the WF rotation, likely because of annual applications of fertilizer S and redistribution of soil S from deeper to shallower depths by the deep-rooted forage crops. Over a rotation cycle, the average annual S rate in treatments that receive fertilizer S, the average annual rate was 10 kg S ha\(^{-1}\) in the WF rotation and 20 kg S ha\(^{-1}\) in the 5 yr rotation. Expected harvest S removals, calculated using average yields from the NPKS treatment from the Breton Classical Plots and typical nutrient concentrations for western Canada (Alberta Agriculture and Forestry 2020) were 9, 13, 14, and 33 kg S ha\(^{-1}\) for wheat

### Table 2. Summary of average total soil 0–15 cm C, N, P, K, S, and pH according to rotation and fertility treatment in the Breton Classical Plots measure on samples taken in 2013.

| Rotation/fertility | 0–15 cm total element mass (Mg ha\(^{-1}\)) | 0–15 cm |  |  |  |  |
|--------------------|------------------------------------------|----------|----------|----------|----------|----------|
|                    | C    | N   | P     | K      | S      | pH     |
| **Wheat–Fallow, WF** |     |     |       |        |        |        |
| NPKS\(^a\)         | 23.0d | 2.37cd | 1.61ab | 4.54ab | 0.53ab | 5.26d   |
| PKS (–N)           | 18.2d | 1.73e  | 1.63ab | 5.27a  | 0.45ab | 5.38bcd |
| NKS (–P)           | 21.7d | 2.11cde| 1.11ab | 3.80abc| 0.50ab | 5.25d   |
| NPS (–K)           | 25.8cd| 2.09cde| 1.73ab | 4.24abc| 0.55ab | 5.39bcd |
| NPK (–S)           | 18.6d | 2.00de | 1.28ab | 5.55a  | 0.45ab | 5.60abcd|
| Manure             | 37.6abc| 3.58abc| 1.81ab | 4.80ab | 0.73ab | 6.01abcd|
| Check\(^b\)        | 18.7d | 1.75e  | 1.14ab | 4.41ab | 0.41b  | 5.82abcd|
| Rotation average    | 23.9B | 2.33B | 1.44A  | 4.89A  | 0.54B  | 5.53B   |
| **5 yr, WOBHH**    |     |       |        |        |        |        |
| NPKS\(^a\)         | 38.2b | 3.56b | 1.46ab | 3.11bc | 0.67a  | 5.74cd  |
| PKS (–N)           | 34.1bc| 3.18bc | 1.64a  | 3.50abc| 0.63ab | 5.93abcd|
| NKS (–P)           | 32.7bc| 2.98bcd| 1.10b  | 3.64ab | 0.72a  | 5.70cd  |
| NPS (–K)           | 37.7b | 3.52b | 1.63a  | 2.58c  | 0.72a  | 5.86bcd |
| NPK (–S)           | 32.8bc| 3.08bcd| 1.49ab | 3.58ab | 0.54ab | 6.15abc |
| Manure             | 46.7a | 4.42a | 1.45ab | 3.64ab | 0.69a  | 6.37a   |
| Check\(^b\)        | 31.2c | 2.89cd| 1.19b  | 3.32abc| 0.56ab | 6.19ab  |
| Rotation average    | 35.8A | 3.32A | 1.42A  | 3.27B  | 0.63A  | 6.00A   |

| Factor             | df  | P value |
|--------------------|-----|---------|
| Rotation           | 1   | ***     |
| Fertility (rotation)| 12  | ***     |

**Adjusted R\(^2\)**

|          | 0.75 | 0.66 | 0.26 | 0.34 | 0.28 | 0.42 |

**Note:** Means within each column, across both rotations, averages that do not share the same lowercase letter are significantly different (\(P < 0.05\); Tukey). Rotation averages that do share the same uppercase letter are significantly different (\(P < 0.05\); Tukey). *, \(P < 0.05\); **, \(P < 0.01\), ***, \(P < 0.001\).

\(^a\)Plot numbers 3 and 9 as labelled at the research site.

\(^b\)Plot numbers 5 and 11 as labelled at the research site.
Table 3. Summary of average wheat yield (grain and straw) and N uptake (grain, straw, and grain + straw) according to rotation and fertility treatment of the Breton Classical Plots over the 2007–2018 growing seasons.

| Rotation/fertility | Yield (kg ha⁻¹) | N uptake (kg N ha⁻¹) |
|-------------------|-----------------|---------------------|
|                   | Grain | Straw | Grain | Straw | Grain + straw |
| Wheat – Fallow, WF |       |       |       |       |               |
| NPKS              | 2785ab | 5018ab | 58bcd | 34ab | 91bcde |
| PKS (−N)          | 704f  | 1718g | 14gh  | 11d  | 26hi  |
| NKS (−P)          | 1845cde | 3585de | 46cdef | 28abc | 74defg |
| NPS (−K)          | 2887ab | 5245a | 63abcd | 34ab | 98abcd |
| NPK (−S)          | 2339bc | 3907cde | 56bcd | 28abc | 84bde |
| Manure            | 1532de | 3003ef | 33efg | 19cd | 52fg |
| Check             | 762f  | 1792g | 14h   | 12d  | 26i   |
| Rotation average   | 1836B | 3467B | 41B   | 24B  | 65B   |
| 5 yr, WOBHH        |       |       |       |       |       |
| NPKS              | 3353a | 4975a | 81a   | 35a  | 116a  |
| PKS (−N)          | 2766b | 4146cd | 61bc  | 27bc | 88cd  |
| NKS (−P)          | 1559cde | 3101ef | 42de  | 27bc | 69ef  |
| NPS (−K)          | 2865b | 4271bcd | 69b   | 33ab | 102abc |
| NPK (−S)          | 2010cd | 3314e | 50cde | 26bc | 76def |
| Manure            | 2934ab | 4642abc | 73ab  | 33ab | 106ab |
| Check             | 1218ef | 2711f | 28fgb | 22c  | 50gh  |
| Rotation average   | 2387A | 3880A | 58A   | 29A  | 87A   |

| Factor             | df     | P value       |
|--------------------|--------|---------------|
| Year               | 10     | 0.050         |
| Year × rotation    | 18     | 0.023         |
| Rotation           | 1      | 0.006         |
| Fertility (rotation) | 12 <0.001 | <0.001 | <0.001 | <0.001 |

Adjusted $R^2$

|             |         |         |
|-------------|---------|---------|
| Year        | 0.81    | 0.79    |
| Year × rotation | 0.85 | 0.79    |
| Rotation    | 0.79    | 0.77    |

Note: Within each column, across both rotations, averages that do not share the same lowercase letter are significantly different ($P < 0.05$; Tukey). Rotation averages that do share the same uppercase letter are significantly different ($P < 0.05$; Tukey).

*Plot numbers 3 and 9 as labelled at the research site.

*Plot numbers 5 and 11 as labelled at the research site.

*The mixed model variance estimate for the year factor was zero, so a P value could not be estimated.

(both WF and 5 yr), oats, barley, and hay (two cuts), respectively.

In both rotations, manure rates were based on target N application rates. Over a rotation cycle, the average annual manure N rate in the relevant treatments for the 5 yr rotation is 35 and 45 kg N ha⁻¹ for the WF rotation. Therefore, less manure is applied to the 5 yr rotation overall, so the greater soil C and nutrient levels in the 5 yr rotation are results of greater net additions from biological fixation.

Fertility treatment yields and soil properties within rotations

By comparing yields and soil nutrient levels between the fertility treatments within rotations, the response of wheat to applied nutrients can be estimated by quantifying yield reductions associated with exclusion of N, P, K, or S in appropriate treatments compared with the NPKS treatment.

WF rotation

Comparing the NPKS and PKS(−N) treatments, exclusion of applied N was associated with a significant reduction in average grain and straw yield (2000 and 4300 kg ha⁻¹, respectively; Table 3); and a significant reduction in average grain, straw and grain + straw N uptake (44, 21, and 65 kg N ha⁻¹, respectively). The low soil N levels in the PKS(−N) treatments were likely a result of biannual removal of grain N without replacement, resulting in net N losses from the soil over time (Table 2).

Comparing the NPKS and NKS(−P) treatments, exclusion of applied P was associated with a significant reduction in average grain and straw yield (900 and
1500 kg ha\(^{-1}\); Table 3), respectively, but observed reductions in average grain, straw and grain + straw N uptake (12, 6, and 18 kg N ha\(^{-1}\), respectively; Table 3), were not significant. Exclusion of P resulted in a slight reduction in total soil P, but the significant yield reductions also suggested a significant reduction in available soil P (not measured). The slight reduction in soil total N associated with the exclusion of applied P is consistent with the reduction in wheat N uptake and net losses from the 0–15 cm depth over time; N not taken up by the crop was likely vulnerable to non-harvest losses such as leaching or denitrification (Table 2). The large reduction in straw yield associated with P exclusion and the associated lower leaf area reduces photosynthetic potential during grain production later in the growing season, but higher N concentration in straw and grain apparently reduced differences in N uptake compared with the NPKS treatment.

Comparing the NPKS and NPK(−K) treatments, exclusion of applied K was not associated with any yield or N uptake reductions (Table 3). Soil total N and K in the NPK(−K) treatment were slightly lower than but not significantly different than the levels in the NPKS treatment (Table 2).

Comparing the NPKS and NPK(−S) treatments, exclusion of applied S was associated with a significant reduction in average straw yield (1100 kg ha\(^{-1}\)) and a minor reduction in grain yields (450 kg ha\(^{-1}\)), average grain, straw and grain + straw N uptake (2, 6, and 8 kg N ha\(^{-1}\), respectively; Table 3). Similar to the effects of P exclusion, the slightly reduced soil N levels are likely a reflection of net N losses from 0 to 15 cm depth over time because N not taken up by the crop is vulnerable to other losses (Table 2). Despite biannual harvest losses of S, soil S levels in the NPK(−S) treatment were only slightly lower than treatments with added S, likely because ammonium sulfate was applied to this treatment prior to 1980 (Dyck et al. 2012).

Comparing the NPKS and manure treatments, the significant reduction in grain and straw yield, and grain N, straw N, and grain + straw N uptake (Table 3) in the manure treatment was difficult to interpret given its superior soil total C and N levels, similar C:N ratio, and similar soil total nutrient levels (Table 2).

5 yr rotation

Comparing the NPKS and PKS(−N) treatments, exclusion of N was associated with a significant reduction in average grain and straw yield (600 and 800 kg ha\(^{-1}\), respectively; Table 3); and a significant reduction in average grain, straw, and grain + straw N uptake (20, 8, and 28 kg N ha\(^{-1}\), respectively; Table 3). Despite a lack of applied N, soil N levels in the PKS(−N) treatment were only slightly lower than the NPKS treatment, likely because of significant biologically fixed N additions from alfalfa in the hay phase (Table 2). The overall average difference in aboveground (grain + straw) wheat N uptake in the two treatments was approximately 40 kg N ha\(^{-1}\), close to the applied N rate of 50 kg N ha\(^{-1}\).

Comparing the NPKS and NKS(−P) treatments, exclusion of P was associated with a significant reduction in average grain and straw yield (both 1800 kg ha\(^{-1}\); Table 3); and a significant reduction in average grain, straw, and grain + straw N uptake (39, 8, and 47 kg N ha\(^{-1}\), respectively; Table 3). The lower levels of soil total N associated with P exclusion were likely a result of greater non-harvest N losses similar to the WF rotation (Table 2), and, perhaps more importantly, reduced biological N fixation in alfalfa during the hay phase of the rotation (see figure 4 in Dyck et al. 2012). The observed reduction in total soil P associated with P exclusion was likely a result of annual harvest losses without replacement.

Comparing the NPKS and NPS(−K) treatments, exclusion of K was associated with a significant reduction in average grain and straw yield (500 and 700 kg ha\(^{-1}\), respectively; Table 3), a significant reduction in grain N uptake (12 kg N ha\(^{-1}\)), and minor reductions in straw and grain + straw N uptake (2 and 14 kg N ha\(^{-1}\), respectively; Table 3). Exclusion of K was not associated with a significant decrease in soil N levels (Table 2), likely because K exclusion did not reduce biological N fixation in alfalfa to the same extent as a P and S exclusion (see figure 4 in Dyck et al. 2012). The observed decrease in soil total K levels was consistent with annual harvest losses from all phases of the rotation without being replaced (Table 2).

Comparing the NPKS and NPK(−S) treatments, exclusion of S was associated with a significant reduction in average grain and straw yield (1300 and 1600 kg ha\(^{-1}\), respectively); and a significant reduction in average grain, straw, and grain + straw N uptake (31, 9, and 40 kg N ha\(^{-1}\), respectively; Table 3). Similar to P exclusion, the lower levels of soil total N associated with S exclusion were likely a result of greater net N losses as in the WF rotation, and, reduced biological N fixation in alfalfa during the hay phase of the rotation (see figure 4 in Dyck et al. 2012). Soil total S level reductions were associated with S exclusion was consistent with annual harvest losses not being offset by added S (Table 2).

Comparing the NPKS and manure treatments, grain and straw yields, and N uptake in grain, straw and grain + straw were not significantly different (Table 3). In the manure treatment, soil total C and N were significantly higher, but the apparent total C : total N ratio and other nutrient levels were not significantly different (Table 2).

Rotation effects on wheat response to applied nutrients

Based on the above observations, there were significant differences in rotations with respect to wheat yield and N uptake response (i.e., increases) to applied nutrients.
Wheat response to applied N was greater in the WF rotation compared with the 5 yr rotation, likely because significant biologically fixed N inputs occur in the previous hay phase of the 5 yr rotation that were made available to the subsequent wheat crop. Mineralized N from the soil total N pool was also likely greater in the 5 yr rotation. The very low yields and N uptake from the control and N exclusion treatment in the WF rotation suggest that long-term export of the N through grain harvesting has exacerbated the observed N deficiency.

Wheat response to applied P was greater in the 5 yr rotation compared with the WF rotation, likely because P is lost through harvest during all phases of the 5 yr rotation and exclusion of P also apparently reduces biological N fixation in alfalfa during the hay phase. Given the similar soil total P levels in all treatments of both rotations, but particularly the NKS(−P) treatments, the greater apparent P deficiency (i.e., response to applied P) in the 5 yr rotation was likely a result of greater P demand under the higher N levels of the 5 yr rotation. The strong response to applied P in both rotations is consistent with other observations across western Canada.

Wheat responded to applied K in the 5 yr rotation, but not in the WF rotation, likely because of persistent net soil K loss from annual harvest removals of all phases, and particularly in the forage phase, of the 5 yr rotation. Furthermore, K demand is likely higher under the higher N levels and productivity of the 5 yr rotation. Wheat has not generally been observed to respond to applied K in western Canada (Karamanos et al. 2013a) because soil levels are generally adequate. These results suggest that long-term intensive rotations, especially containing forages, will eventually draw down soil K to critical levels if not replaced.

Wheat response to applied S was greater in the 5 yr rotation compared with the WF rotation, despite higher levels of total soil S in the NPK(−S) treatment of the 5 yr rotation compared with the WF rotation, suggesting a greater S demand under the higher N levels of the 5 yr rotation. The higher levels of total soil S in the 5 yr rotation were also likely a result of greater annual applications prior to 1980 prior to implementation of the S exclusion treatment (see Table 1 in Dyck et al. 2012). Similar to P, wheat response to applied S in the 5 yr rotation was apparently influenced by reduced biological N fixation associated with S exclusion during the hay phase. In both rotations, wheat response to S was comparable although slightly lower than response to P. Wheat has not generally been observed to respond to applied S in western Canada (Grant et al. 2004; Karamanos et al. 2013b), but there have been reports of wheat response to applied S in a dark gray Luvisol in Saskatchewan (Malhi et al. 2009). These results suggest that long-term intensive rotations, especially containing forages, will eventually draw down soil S to critical levels if not replaced.

Response to applied manure was greater in the 5 yr rotation compared with the WF rotation, but the reason for this rotation difference was unclear and differences in total soil C and nutrients do not indicated any deficiencies.

Conclusion
The results presented in this paper highlight the importance of rotation-based nutrient management. The 5 yr cereal–forage rotation at Breton is an example of a moderately intense rotation with diverse nutrient requirements. The greater response of the 5 yr rotation to applied P, K, and S compared with the WF rotation are a reflection of high P, K, and S harvest losses from the alfalfa–brome forage phase of the rotation that have carried over to the wheat phase. These responses are enhanced by additional biologically fixed N, and greater residue returns in the 5 yr rotation, increasing total soil N and C, increasing the yield potential of wheat due to greater available N and possibly greater plant-available water. In terms of management applications of the results presented in this work, nutrient removals over each rotation cycle should be assessed and, at minimum, replaced with fertilizer or organic sources.

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