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Changes in Soil Phosphorus Pools in Long-Term Wheat-Based Rotations in Saskatchewan, Canada With and Without Phosphorus Fertilization

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Phosphorus (P) is an essential nutrient for all organisms, and many crops require P fertilization for optimum yield. However, there are concerns about the P in agriculture, including the sustainability of phosphate sources for fertilizers and water quality problems from P loss in runoff from agricultural lands. Most crops do not use all of the P added each year as fertilizer, leaving residual soil P that could potentially be used by subsequent crops, minimizing the need for additional fertilization. However, more information is needed to understand soil residual P pools, and their availability to crops. In Swift Current, SK, Canada, a long-term study was initiated in 1967, with four wheat-based rotations [including continuous wheat (CW), fallow-wheat-wheat (FWW), fallow-wheat (FW) and lentil-wheat (WL), with P fertilization and with or without nitrogen (N) fertilization. In 1995, P fertilization ceased on subplots in the CW and FWW rotations, and in 2008 for the FW and WL rotations. This study examined changes in soil P pools (total P, organic P, and Olsen P) from 1995 to 2015 for CW and FWW rotations and from 2008 to 2016 for FW and WL rotations, plus crop yield and grain and straw N and P concentrations. Long-term P addition increased concentrations of soil total and Olsen P in FWW, CW and FW rotations, particularly in plots without N fertilization. However, calculated P depletions based on fertilizer addition and crop P removal were negative only for plots without N fertilization. Cessation of P fertilization reduced concentrations of soil total and Olsen P, especially in plots with N fertilization. Annual yields were affected more by N fertilization and precipitation than P fertilization. Grain and straw P concentrations were not significantly reduced with short-term P cessation in FW and WL rotations, but were reduced with longer-term P fertilizer cessation in FWW and CW rotations.

Keywords: fertilizer cessation, legacy phosphorus, drawdown, organic phosphorus, total phosphorus, Olsen phosphorus, phosphorus use efficiency

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INTRODUCTION

Phosphorus (P) is an essential element for all organisms, including crops. In order to maximize crop yields, chemical and/or organic (e.g., manure) fertilizers have been added to soils for decades or more to increase soil P concentrations (Way, 1850; Rubæk et al., 2013; Withers et al., 2019). Intensification of agriculture in the mid-to late-20th century substantially increased P fertilizer use, often far beyond what was required to replace P removed in crops and resulting in high P concentrations in many agricultural soils (MacDonald et al., 2011; Bruulsema et al., 2019; Withers et al., 2019). These high soil P concentrations are often maintained by producers to minimize productivity risks related to soil P fertility (Withers et al., 2019). However, application of fertilizer P beyond the agronomic optimum can result in P loss from land to water, by erosion of particulates or through dissolved P in runoff or drainage waters (Ulén and Jakobsson, 2005; Cade-Menun et al., 2013; Schoumans et al., 2014; Cade-Menun et al., 2017; Liu et al., 2019). This P loss is a major contributor to eutrophication and water quality problems (Sharpley et al., 1994) and efforts are underway in many countries to manage the P that has accumulated in soils (Withers et al., 2019). It is also widely recognized that the rock phosphate used to produce chemical P fertilizers is a finite resource requiring careful management for long-term sustainability (Djodjic et al., 2005; Rubæk et al., 2013; Withers et al., 2019).

Application of P fertilizers is often based on soil tests, which need to be specifically calibrated to crops and soils. And it is widely recognized that not all fertilizer P added each year is used by that year's crops, even when applied conservatively based on soil test recommendations (Sattari et al., 2012). Instead, P in excess of crop requirements is retained in soil by sorption and/or precipitation reactions, increasing concentrations of soil test P and total P in soils over time (Selles et al., 2011; Rubæk et al., 2013; Rowe et al., 2016; Cade-Menun et al., 2017). This residual, or legacy, P is defined as the difference between inputs (from fertilizer products, deposition and weathering) and outputs (removal in harvested crops or through P loss in runoff or erosion; Sattari et al., 2012), and needs to be carefully managed to reduce the environmental risk. This includes management practices to reduce P transport (e.g. erosion controls), but also requires management to reduce soil test P concentrations when they exceed agronomic optima (Withers et al., 2019). There is also growing recognition that legacy P could be more available to crops than originally thought, reducing or even replacing fertilizer P applications and thereby conserving finite rock phosphate sources (Sattari et al., 2012; Rubæk et al., 2013; Rowe et al., 2016; Withers et al., 2019).

Fertilizer cessation is a key practice to draw down legacy P concentrations to agronomically-optimal levels to reduce the potential for P loss. However, guidelines are needed to manage fertilizer cessation, in order to reduce soil test P concentrations without any negative impacts on yield (Withers et al., 2019). This requires data from fertilizer cessation studies from different crops grown in a wide range of conditions, including: the time required to draw down soil test P concentrations; changes in soil P pools beyond soil test P, such as total P and organic P; and the effects of different management practices on the rate of P drawdown. Long-term studies are an essential source for this information, particularly with respect to the time frame needed to reduce soil P concentrations, which will vary with factors including soil type and texture, initial soil P concentrations, and other influences on crop health (Rubæk et al., 2013; Cade-Menun et al., 2017; Liu et al., 2019; Appelhans et al., 2020).

In Swift Current, SK, Canada, a long-term study of wheat-based crop rotations with P fertilization, and with and without N fertilization, was established in 1967; subplots without P fertilization were established in 1995 for rotations with wheat every year (continuous wheat; CW) and with fallow every third year (fallow-wheat-wheat, FWW; Selles et al., 1995; Selles et al., 2011). In 2005, soil test P concentrations had decreased in P cessation plots for CW and FWW rotations with N fertilization compared to plots with continued P fertilizer application (Selles et al., 2011). Grain production was reduced by 10% for the CW wheat with P fertilizer cessation, but there was no effect on yield for the FWW rotation, suggesting that legacy P was retained in soils in plant-available forms for many years after fertilizer application (Selles et al., 2011). However, only changes in soil test (Olsen) P concentrations were determined, without examining changes in other soil P pools.

The objective of this study is to continue the work published in Selles et al. (2011), to understand the long-term effects of continued P fertilization versus P fertilizer cessation on wheat-based crop rotations in the Northern Great Plains of North America. Fertilizer cessation plots were established for two additional crop rotations in 2008: alternating fallow and wheat (FW) rotations, and lentil-wheat (WL) rotations. Soil test (Olsen) P was monitored for an additional decade (2006–2015) in the same CW and FWW rotations used by Selles et al. (2011) and in the new plots (2008–2016). In addition to Olsen P, soil total P (TP) and organic P (Org P) were determined each year from 1995 to 2015 for CW and FWW rotations, and from 2008 to 2016 for WL and FW rotations. It was hypothesized that a) concentrations of Olsen P, TP and Org P would increase with continued P fertilization for all crop rotations and decrease when P fertilization stopped; b) Olsen P concentrations would change more with continued fertilization or fertilizer cessation than TP and Org P concentrations; c) decreases in Org P after fertilization cessation would indicate mineralization of Org P to meet crop P demands; and d) crop yields and grain P concentrations would decrease with P fertilizer cessation.

MATERIALS AND METHODS

Field Sites and Management

Samples were collected from an experiment established in 1967 on Orthic Brown Chernozem (Canadian classification; Aridic Haploboroll, USDA; Haplic Kastanozem, FAO) soils at the Agriculture and Agri-Food Canada Swift Current Research and Development Centre in Saskatchewan, Canada (latitude 50°170′N, longitude 107°480′W). More details are available in Selles et al. (1995, 2011), Liu et al. (2015), and Chen et al. (2021). This study used plots for four crop rotations: CW, FWW, FW and WL. The CW, FW and FWW rotations were established in 1967; the WL plots were established in 1982. All phases for each rotation were present each year, with three replicate plots per treatment. From establishment, plots were fertilized with 10 kg P ha^{-1} yr^{-1} (monoammonium phosphate, MAP) and either a) no N fertilizer (the -N+P treatment); or b) 32–50 kg N ha^{-1} yr^{-1} (ammonium nitrate, NH_4NO_3 from 1967 to 2007, urea from 2008; the +N+P treatment), with N application rates based on soil testing each spring. No fertilizer was applied during the fallow phase of FW and FWW rotations, and no N fertilizer was applied

TABLE 1 | Phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the fallow-wheat-wheat (FWW) rotation, analyzed by fertilizer treatment, for 1995–2015. Values are means (std. err); n = 150; different letters among treatments for each P pool indicate significantly different means (α = 0.05).

			Fertilizer treatment					
P Pool	**Units**	**Depth (cm)**	**+N+P**	**+N-P**	**-N+P**	**-N-P**	**N only**	**None**
TP	mg kg^{-1}	0–7.5	573.3 a (4.51)	536.9 b (3.36)	581.8 a (4.97)	542.5 b (4.09)	511.7 c (4.12)	497.2 c (3.61)
TP	mg kg^{-1}	7.5–15	493.5 a (5.28)	473.9 a (4.82)	477.4 ab (5.57)	471.9 b (4.81)	464.9 b (4.56)	461.5 b (4.03)
TP	kg ha^{-1}	0–15	949.0 a (8.28)	900.9 b (7.03)	956.7 a (8.35)	919.0 bc (6.69)	881.6 cd (7.37)	866.8 d (6.47)
TP Δ[a]	kg ha^{-1}	0–15	24.4 ab (24.6)	–12.7 ab (25.8)	57.1 a (29.4)	12.3 ab (19.6)	–56.4 b (26.1)	–11.5 ab (13.9)
Org P	mg kg^{-1}	0–7.5	292.7 (4.66)	293.0 (4.27)	292.3 (4.54)	294.3 (4.20)	281.7 (4.31)	284.3 (4.00)
Org P	mg kg^{-1}	7.5–15	282.9 (5.08)	286.3 (5.29)	278.1 (4.90)	277.9 (4.50)	271.6 (4.39)	279.1 (4.30)
Org P	kg ha^{-1}	0–15	516.0 (7.82)	519.7 (7.43)	519.0 (6.56)	519.9 (5.83)	501.2 (6.98)	511.3 (7.03)
Org P Δ[a]	kg ha^{-1}	0–15	70.8 (26.6)	14.7 (28.2)	36.0 (20.1)	6.97 (17.4)	26.8 (26.2)	13.0 (18.9)
Org P	% TP	0–7.5	51.2 bc (0.77)	54.7 a (0.75)	50.7 c (0.84)	54.3 ab (0.71)	55.4 a (0.87)	57.6 a (0.86)
Org P	% TP	7.5–15	57.6 (0.94)	60.5 (0.96)	58.7 (0.94)	59.4 (0.96)	59.0 (0.98)	60.7 (0.87)
Olsen P	kg ha^{-1}	0–15	27.6 b (1.05)	16.5 d (0.58)	34.7 a (1.05)	23.0 c (0.65)	9.93 e (0.37)	9.80 e (0.45)
Olsen P Δ[a]	kg ha^{-1}	0–15	15.6 a (3.71)	–2.53 b (1.80)	17.1 a (3.69)	2.95 b (2.06)	0.23 b (1.10)	0.95 b (1.80)
P Depletion[b], mean kg ha^{-1}			1.94 c (0.39)	10.2 a (0.32)	–0.08 c (0.37)	8.28 b (0.35)	7.70 b (0.36)	7.44 b (0.24)
P Depletion[b], cumul. kg ha^{-1}			27.2 c (6.69)	142.1 a (4.39)	–1.13 d (–4.51)	115.9 b (3.28)	107.8 b (3.46)	104.2 b (2.90)

[a]*Net change, 1995–2015.*
[b]*P depletion, grain P minus fertilizer P.*

TABLE 2 | Phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the continuous wheat (CW) rotation, analyzed by fertilizer treatment, for 1995–2015. Values are means (std. err); n = 63; different letters among treatments for each P pool indicate significantly different means (α = 0.05).

			Fertilizer treatment			
Phosphorus pool	**Units**	**Depth (cm)**	**+N+P**	**+N-P**	**-N+P**	**-N-P**
TP	mg kg^{-1}	0–7.5	592.7 ab (7.36)	552.1 c (6.32)	617.8 a (8.89)	573.9 bc (6.88)
TP	mg kg^{-1}	7.5–15	475.0 b (8.40)	472.7 b (6.42)	509.5 a (9.14)	495.3 a (8.92)
TP	kg ha^{-1}	0–15	892.9 c (12.2)	861.3 c (9.15)	1,002.3 a (14.2)	954.0 b (12.8)
TP Δ[a]	kg ha^{-1}	0–15	66.6 ab (50.0)	9.90 ab (51.8)	159.6 a (36.9)	–43.2 b (45.0)
Org P	mg kg^{-1}	0–7.5	315.1 (6.11)	326.3 (7.02)	287.1 (6.40)	286.6 (7.73)
Org P	mg kg^{-1}	7.5–15	273.1 (5.25)	296.3 (7.13)	283.9 (6.41)	261.2 (5.92)
Org P	kg ha^{-1}	0–15	495.4 (8.08)	526.3 (10.8)	513.0 (8.90)	489.8 (10.1)
Org P Δ[a]	kg ha^{-1}	0–15	37.4 (24.2)	12.1 (38.7)	2.83 ab (33.6)	8.50 (27.7)
Org P	% TP	0–7.5	53.7 (1.23)	59.4 (1.39)	47.0 (1.28)	50.3 (1.42)
Org P	% TP	7.5–15	58.1 (1.16)	62.9 (1.39)	56.6 (1.45)	54.0 (1.64)
Olsen P	mg kg^{-1}	7.5–15	6.63 b (0.78)	4.46 bc (0.33)	11.8 a (1.13)	3.99 c (0.32)
Olsen P	% TP	7.5–15	1.34 b (0.14)	0.96 bc (0.08)	2.26 a (0.20)	0.81 c (0.06)
Olsen P Δ[a]	kg ha^{-1}	0–15	15.4 b (2.17)	–8.13 c (2.19)	30.3 a (5.18)	–2.05 c (2.87)
P Depletion[b], mean kg ha^{-1}			1.71 b (0.39)	8.12 a (0.43)	–1.70 c (0.35)	6.93 a (0.36)
P Depletion[b], cumul. kg ha^{-1}			35.9 b (1.73)	170.6 a (1.73)	–35.6 c (1.73)	145.6 a (1.73)

[a]*Net change, 1995–2015.*
[b]*P depletion, grain P minus fertilizer P.*

to the lentil phase of the WL plots (P fertilizer was applied to both the wheat and lentil phases). In addition, the FWW rotation had a treatment receiving no P fertilization from establishment (the "N only" treatment). In 1995 for the CW and FWW rotations and in 2008 for the FW and WL rotations, sub-plots without P fertilization were established on all plots receiving P fertilizer, hereby designated as the +N-P and -N-P treatments. In the sub-plots of the N only treatment, N application stopped, resulting in no fertilization of any kind (the "None" treatment).

For most years, crops were seeded in May and harvested in August. Weed management was by mechanical tillage and herbicides, using locally recommended rates and methods. Summer fallow plots for the FW and FWW rotations were managed with additional tillage and herbicide applications. Fertilizer N was broadcast before seeding, while fertilizer P was seed-placed.

Sample Collection and Processing

Small areas (2.32 m^2) in each plot were harvested manually to determine yield and to analyze for grain and straw N and P, with plant heights and number of plants also recorded. The remaining grain was harvested with a conventional combine; straw was chopped and spread on the plots. After drying at 70°C, weights

TABLE 3 | Soil phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the fallow-wheat (FW) rotation, analyzed by fertilizer treatment, for 2008–2016. Values are means (std. err); $n = 48$; different letters among treatments for each P pool for each depth indicate significantly different means (Tukey HSD; $\alpha = 0.05$).

			Treatment	
Phosphorus pool	**Units**	**Depth (cm)**	**+N+P**	**+N-P**
TP	mg kg^{-1}	0–7.5	584.3 a (6.83)	564.4 b (546)
TP	mg kg^{-1}	7.5–15	509.6 (8.64)	494.5 (8.08)
TP	kg ha^{-1}	0–15	996.6 a (10.8)	965.2 b (8.89)
TP Δ[a]	kg ha^{-1}	0–15	21.2 (28.9)	3.84 (23.7)
Org P	mg kg^{-1}	7.5–15	280.6 (8.76)	280.7 (9.10)
Org P Δ[a]	kg ha^{-1}	0–15	–30.3 (31.3)	1.40 (28.4)
Olsen P	mg kg^{-1}	0–7.5	31.0 a (1.00)	26.0 b (0.70)
Olsen P	mg kg^{-1}	7.5–15	14.6 (1.04)	12.3 (0.97)
Olsen P	kg ha^{-1}	0–15	40.4 a (1.63)	34.0 b (1.17)
Olsen P Δ[a]	kg ha^{-1}	0–15	19.5 (3.41)	12.6 (2.18)
Olsen P	% TP	0–7.5	5.30 a (016)	4.62 b (0.13)
Olsen P	% TP	7.5–15	2.81 (0.18)	2.44 (0.17)
P Depletion[b], mean kg ha^{-1}			3.25 b (0.70)	11.7 a (0.76)
P Depletion[b], cumul. kg ha^{-1}			13.0 b (1.80)	46.8 a (2.63)

[a]*Net change, 2008.*
[b]*P depletion, grain P minus fertilizer.*

TABLE 4 | Soil phosphorus (P) concentrations in various pools (TP, total P; Org P, organic P; Olsen P, bicarbonate-extractable P) for the wheat-lentil (WL) rotation, analyzed by fertilizer treatment, for 2008–2016. Values are means (std. err); $n = 48$.

			Treatment	
Phosphorus pool	**Units**	**Depth (cm)**	**+N+P**	**+N-P**
TP	mg kg^{-1}	0–7.5	659.1 a (9.17)	616.6 b (8.98)
TP	mg kg^{-1}	7.5–15	531.4 (8.80)	510.4 (9.85)
TP	kg ha^{-1}	0–15	1,041.7 a (12.9)	987.4 b (14.8)
TP Δ[a]	kg ha^{-1}	0–15	–25.4 (38.1)	–59.2 (34.2)
Org P	mg kg^{-1}	0–7.5	328.9 (8.96)	329.5 (7.78)
Org P	mg kg^{-1}	7.5–15	307.1 (7.38)	306.6 (7.32)
Org P	kg ha^{-1}	0–15	560.9 (12.5)	560.9 (11.1)
Org P Δ[a]	kg ha^{-1}	0–15	–31.4 (16.2)	–30.1 (31.0)
Org P	% TP	0–7.5	50.5 (1.85)	53.9 (1.54)
Org P	% TP	7.5–15	58.1 (1.40)	60.7 (1.58)
Olsen P	mg kg^{-1}	0–7.5	37.9 a (1.66)	26.3 b (1.09)
Olsen P	mg kg^{-1}	7.5–15	10.0 (0.88)	8.12 (0.62)
Olsen P	kg ha^{-1}	0–15	39.4 a (1.87)	28.5 b (1.19)
Olsen P Δ[a]	kg ha^{-1}	0–15	16.2 a (4.20)	3.70 b (2.86)
Olsen P	% TP	0–7.5	5.77 a (0.25)	4.30 b (0.17)
Olsen P	% TP	7.5–15	1.87 (0.15)	1.58 (0.11)
Wheat P Depletion[b], mean, kg ha^{-1}			7.14 b (1.31)	13.9 a (1.11)
Lentil P Depletion[b], mean, kg ha^{-1}			–0.60 b (0.97)	9.09 a (0.95)
P Depletion[b], cumul. kg ha^{-1}			26.2 b (3.94)	92.1 a (1.92)

[a]*Net change, 2008–2016.*
[b]*P depletion, grain P minus fertilizer.*

were recorded and then grain and straw samples were ground. See Selles et al. (2011) for more details.

Post-harvest annually (October-November), three soil cores (10-cm diameter) per plot per treatment were collected, which were divided into surface (0–7.5 cm) and subsurface (7.5–15 cm) depths and composited into a single sample per depth per treatment plot. Samples were air-dried, sieved (<2 mm) and stored in paper envelopes at room temperature until chemical analyses. Prior to 2008, soil samples were not collected from fallow plots; from 2008 onward, all plots were sampled each year. Soil samples were archived for CW and FWW plots from 1995 and from FW and WL from 2008.

Laboratory Analysis

Soil P Pools

Bicarbonate-extractable (Olsen) P was extracted and analyzed colorimetrically in each collection year (Olsen et al., 1954; Hamm et al., 1970). Analysis for other P pools described below was done in 2008/2009 on archived samples from 1995 to 2007, and in the year following sample collection from 2008 onward. Total P (TP) was determined by digestion (Parkinson and Allen, 1975) and total organic P (Org P) was determined by the ignition method (Saunders and Williams, 1955), both with colorimetric analysis (Murphy and Riley, 1962). Bulk density data were collected for the main plots in 2021 and were used to convert chemical data from concentrations (mg kg^{-1}) to stocks of each P pool (kg ha^{-1}) for the 0–15 cm depths. There were no significant differences in bulk density for treatments within a single rotation, but bulk densities varied among rotations, especially for the 0–7.5 cm depth (**Supplementary Table S1**). As such, the bulk densities determined for each plot were used for calculations for that plot, rather than a single bulk density value for all treatments, as was used by Selles et al. (2011); however, the same bulk density was used for each plot for all years. Bulk densities were not measured in the sub-plots, and were assumed to be the same as the main plots for each treatment.

Plant Analysis and Yield Data Collection

Grain and straw samples were ground and analyzed for total P and total N by Kjeldahl digestion and colorimetric analysis (Murphy and Riley 1962; Starr and Smith, 1978).

Calculations

Data from the FWW and CW rotations from 1995 to 2015 were grouped in 3-yr blocks for a cumulative year (e.g., 1995, 1996 and 1997 were grouped into the cumulative year "1997," to include all phases of the FWW rotation for each plot. Data from the FW and WL rotations from 2008 to 2016 were similarly grouped into 2-yr blocks. Net changes in total P, organic P and Olsen P (0–15 cm, kg ha^{-1}) were determined by subtracting soil concentrations for each plot per treatment per year for the first cumulative year for each rotation (1997 for FWW and CW; 2010 for FW and WL) from the last cumulative year for each rotation (2015 for FWW and CW; 2016 for FW and WL). For each plot P, depletion was determined by subtracting the P added as fertilizer (kg ha^{-1}) from grain P concentration (kg ha^{-1}); cumulative P depletion was determined by adding annual P depletion for each plot. Straw P concentration was not included in calculations of P depletion because straw was left on each plot post-harvest.

TABLE 5 | Soil organic phosphorus (P) concentrations for the fallow-wheat (FW) rotation for which there was a significant treatment*date interaction by ANOVA, analyzed by fertilizer treatment, for 2008–2016. Values are means (std. err.); n = 12; different letters among treatments for each P pool for each depth indicate significantly different means (Tukey HSD; α = 0.05).

			Year			
Phosphorus pool	**Depth (cm)**	**Treatment**	**2010**	**2012**	**2014**	**2016**
Organic P (mg kg^{-1})	0–7.5	+N+P	289.5 ab (15.3)	269.8 ab (13.6)	306.8 ab (18.6)	277.8 ab (8.22)
		+N-P	323.4 a (19.6)	300.2 ab (10.5)	272.9 ab (12.5)	260.9 b (10.3)
Organic P (kg ha^{-1})	0–15	+N+P	511.4 abc (23.0)	515.4 abc (23.3)	548.5 ab (22.3)	493.6 bc (15.4)
		+N-P	522.5 abc (26.8)	569.5 a (22.7)	480.5 c (19.2)	511.4 abc (15.5)
Organic P (% Total P)	0–7.5	+N+P	47.6 cd (2.39)	47.2 cd (2.10)	53.6 abc (3.03)	47.8 bcd (1.87)
		+N-P	55.7 a (3.52)	54.3 ab (1.38)	48.9 bcd (2.38)	46.3 d (1.66)
Organic P (% Total P)	7.5–15	+N+P	56.4 xy (3.58)	56.5 xy (2.58)	56.0 xy (2.10)	50.8 y (2.07)
		+N-P	53.0 xy (2.99)	64.4 x (3.43)	51.7 y (2.21)	57.4 xy (1.89)

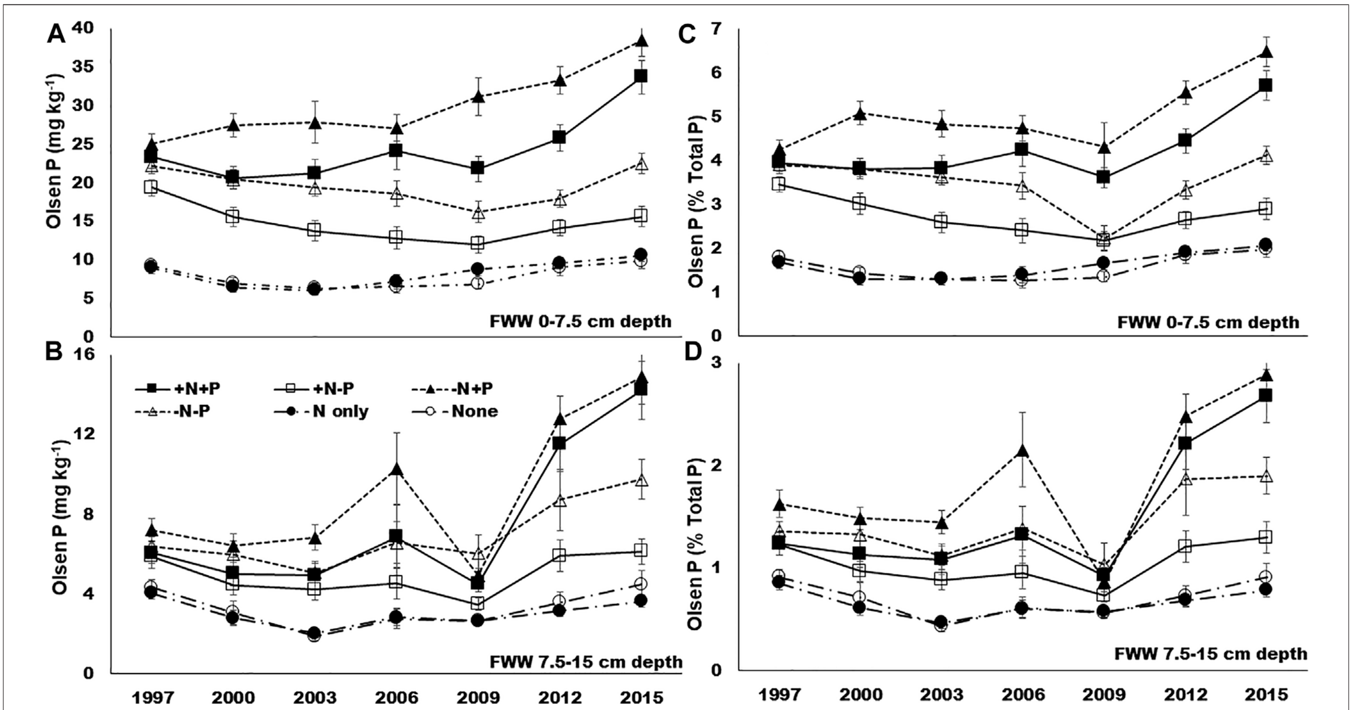

FIGURE 1 | Olsen P concentrations with a significant year*treatment interaction with ANOVA, for the fallow-wheat-wheat (FWW) rotation. Values are means ± standard error. Olsen P concentration (mg kg^{-1}), **(A)** 0–7.5 cm depth and **(B)** 7.5–15 cm depth; and Olsen P concentration as a percentage of total P concentration, **(C)** 0–7.5 cm depth and **(D)** 7.5–15 cm depth. Statistically significant differences among means (Tukey HSD; α = 0.05) are shown in **Supplementary Table S6**.

Statistical Analyses

Data were tested for normality with the Shapiro-Wilks test and transformed as needed, using log(n + 0.5); means reported in figures and tables are from untransformed data. Two-factor analysis of variance (ANOVA) was conducted (treatment, date and the treatment*date interaction) with a standard least squares model, followed by Tukey's highest significant differences (HSD) tests. Statistical analyses were performed using JMP (SAS Institute, v. 5.1), with α = 0.05. The two soil depths were not compared to each other, and were analyzed separately by the same statistical methods. Rotations were also not compared statistically to one another.

RESULTS

Soil Total P

For all rotations and depths, there were no significant interactions of treatment*year for TP (mg kg^{-1}, 0–7.5 cm and 7.5–15 cm; kg ha^{-1}, 0–15 cm), but treatment was significant for most depths and rotations and year was also significant in many cases (**Supplementary Table S2**). For all rotations, mean TP concentrations ranged from 497.2 to 659.1 mg kg^{-1} at 0–7.5 cm, from 461.5 to 531.4 mg kg^{-1} at 7.5–15 cm, and TP stocks ranged from 861.3–1,041.7 kg ha^{-1} for 0–15 cm (**Tables**

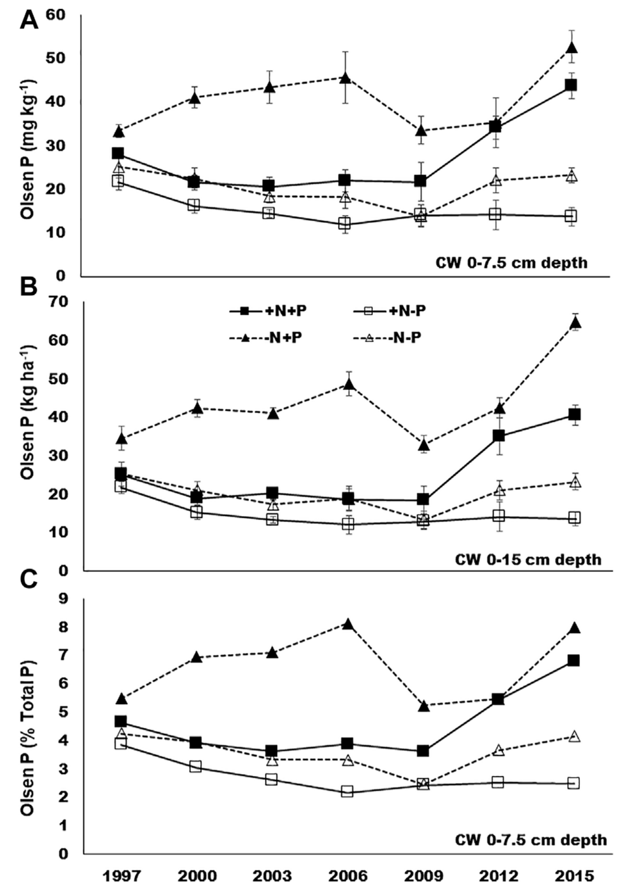

FIGURE 2 | Olsen P concentrations significant year*treatment interaction with ANOVA, for the continuous wheat (CW) rotation. Values are means ± standard error. **(A)** Olsen P concentration (mg kg^{-1}), 0–7.5 cm depth; **(B)** Olsen P concentration (kg ha^{-1}), 0–15 cm depth; and **(C)** Olsen P concentration as a percentage of total P concentration, 0–7.5 cm depth. Statistically significant differences among means (Tukey HSD; α = 0.05) are shown in **Supplementary Table S7**.

1–4). For all rotations, soil TP concentrations in the treatments fertilized with P were significantly greater than those for the treatments without P at 0–7.5 cm depth. For the FWW rotation, TP concentrations for the treatments not receiving any P from 1967 (N only and None) were significantly lower than all other treatments at 0–7.5 cm. There were significant differences in TP concentrations among years for all rotations for all depths, but there are no clear patterns by year (**Supplementary Tables S3–S5**). The means per year were calculated as the average for all treatments for each rotation within that year, despite the wide range in TP values among treatments. As such, caution should be used when comparing among years for each rotation, and the results are included with the Supplemental Materials for reference only. The main manuscript will focus on differences among treatments, and on the net change over time for each treatment for each rotation, on a kg ha^{-1} basis. For the FWW rotation, the net change in TP stock was positive for the +N+P, -N+P and -N-P rotations, indicating increased P concentrations over time, and was negative for the +N-P, N only and None treatments, indicating a net loss. However differences were only significant between the -N+P and N only treatments (**Table 1**). For the CW rotation, the net change in TP stock was negative only for the -N-P treatment, with significant differences only between the -N+P and -N-P treatments (**Table 2**). For the FW rotations, the net change in TP stock was positive for both treatments, and not significantly different (**Table 3**), while for the WL rotation the net change in TP stock was negative, but with no significant difference between treatments.

Soil Organic P

There were no significant interactions of treatment*year for Org P (mg kg^{-1}, 0–7.5 cm and 7.5–15 cm; kg ha^{-1}, 0–15 cm) for the FWW, CW and WL rotations, but there were significant interactions for the FW rotation (**Supplementary Table S2**). For the FWW rotation, there were no significant differences among treatments at either depth for mean Org P concentrations or mean Org P stocks (**Table 1**). When Org P was expressed as % TP, at 0–7.5 cm it was significantly higher in the N only, None and +N-P treatments than -N+P and +N+P and there were no significant differences among treatments at the 7.5–15 cm depth. The net change in Org P stock was positive for all treatments, with no significant differences among treatments. There were significant differences in Org P with year (**Supplementary Table S3**), but as noted for TP, there are no clear trends.

In the CW and WL rotations, there were no significant differences among treatments for mean Org P as concentrations or as % TP at either depth or for Org P stocks at 0–15 cm (**Tables 2**, **4**). There were significant differences with year for the CW rotation for all Org P pools, but no clear trends (**Supplementary Table S4**), and the net change in Org P stock was positive for all treatments (**Table 2**). For the WL rotation, there were no significant differences with year for any Org P pools, and the net change in Org P stock was negative for WL (**Table 4**; **Supplementary Table S4**).

For the FW rotation, there were significant treatment*year interactions for Org P concentrations at 0–7.5 cm, Org P stock at 0–15 cm, and for Org P (% TP) for both depths (**Supplementary Table S2**). At 0–7.5 cm, Org P concentrations were significantly higher in the 2010 +N-P soils than in the 2016 +N-P soils (**Table 5**). At the 7.5–15 cm depth, there were no differences between treatments for concentration but as a proportion of TP values were significantly higher in 2012 +N-P soils than the 2014 +N-P soils and the 2016 +N+P soils (**Table 5**). The net change in Org P stock was negative for the +N+P treatment and positive for the +N-P treatment, but the differences were not statistically significant (**Table 3**).

Soil Olsen P

There were significant treatment*year interactions for ANOVAs of Olsen P concentrations in mg kg^{-1} or as % TP for the 0–7.5 cm and 7.5–15 cm depths for the FWW rotation and for the 0–7.5 cm (mg kg^{-1} and as % TP) and for Olsen P stocks (kg ha^{-1}) at 0–15 cm for the CW rotation, but no significant treatment* year interactions for Olsen P for the FW and WL rotations

TABLE 6 | Grain and straw yield, grain and straw nitrogen (N) and grain and straw phosphorus (P), analyzed by fertilization treatment. Rotations are fallow-wheat-wheat (FWW), continuous wheat (CW), fallow-wheat (FW) and wheat-lentil (WL). Different letters for treatments within each rotation indicate significant differences (α = 0.05); n = 126 for FWW; n = 63 for CW and n = 24 for FW and WL (wheat and lentil).

Rotation	Treatment	Grain yield Mg ha^{-1}	Straw yield Mg ha^{-1}	Grain N kg ha^{-1}	Grain P kg ha^{-1}	Straw N kg ha^{-1}	Straw P kg ha^{-1}
FWW	+N+P	2.75 a (0.09)	4.77 a (0.16)	68.4 a (2.13)	11.4 a (0.37)	20.0 a (0.90)	2.31 a (0.13)
	+N-P	2.61 a (0.08)	4.15 ab (0.15)	64.8 a (2.03)	10.2 ab (0.32)	17.3 a (0.82)	1.71 b (0.11)
	-N+P	2.17 bc (0.09)	3.42 cd (0.18)	47.5 b (2.10)	9.37 cd (0.37)	10.7 b (0.62)	1.86 b (0.11)
	-N-P	2.02 c (0.09)	3.10 cd (0.18)	44.5 b (2.16)	8.42 cd (0.34)	10.5 b (0.68)	1.54 bc (0.11)
	N only	2.38 ab (0.07)	3.67 bc (0.13)	62.9 a (1.88)	8.15 cd (0.27)	17.2 a (0.70)	1.19 cd (0.07)
	None	1.98 c (0.07)	2.87 d (0.11)	48.1 b (1.83)	7.44 d (0.24)	11.1 c (0.54)	1.05 d (0.06)
CW	+N+P	2.44 a (0.10)	3.97 a (0.17)	59.7 a (2.28)	10.8 a (0.41)	18.0 a (1.14)	2.42 a (0.22)
	+N-P	2.08 b (0.08)	3.42 b (0.15)	51.5 b (2.25)	8.21 b (0.37)	16.3 a (0.91)	1.67 b (0.14)
	-N+P	1.58 c (0.06)	2.09 c (0.08)	33.1 c (1.26)	7.68 b (0.30)	6.59 b (0.27)	2.03 ab (0.14)
	-N-P	1.45 c (0.07)	1.92 d (0.10)	31.7 c (1.92)	6.93 b (0.36)	6.29 b (0.40)	1.49 b (0.11)
FW	+N+P	3.33 (0.14)	5.57 (0.32)	73.8 (3.17)	12.7 (0.69)	18.6 (1.35)	2.15 (0.25)
	+N-P	3.04 (0.16)	4.95 (0.38)	69.1 (3.34)	11.7 (0.76)	16.0 (1.47)	1.69 (0.21)
WL wheat	+N+P	3.51 (0.27)	5.57 (0.55)	90.2 (6.89)	15.4 (1.22)	21.1 (1.85)	2.94 (0.39)
	+N-P	3.24 (0.24)	4.62 (0.46)	80.5 (5.93)	13.9 (1.11)	19.7 (3.48)	2.46 (0.41)
WL lentils	-N+P	2.22 (0.26)	4.04 (0.39)	85.2 (10.3)	8.59 (1.00)	47.4 (5.70)	4.41 (0.58)
	-N-P	2.44 (0.25)	3.80 (0.28)	92.9 (9.69)	9.09 (0.95)	40.2 (4.37)	3.51 (0.40)

(**Supplementary Table S2**). In the FWW rotation, Olsen P concentrations for the N only and None treatments were below 10 mg kg^{-1} and were generally lower than for the other treatments at 0–7.5 cm depth, especially from 2006 to 2015, when concentrations for the +N+P and -N+P treatments were 25–35 mg kg^{-1} (**Figure 1A**; **Supplementary Table S6**). At 7.5–15 cm, there were no significant differences among treatments from 1997 to 2009, with concentrations below 10 mg kg^{-1} (**Figure 1B**; **Supplementary Table S6**). However, in 2012 and 2015, Olsen P concentrations for the N only and None treatments were significantly lower than other treatments at 7.5–15 cm depth. When expressed as % TP, trends were similar to those for concentration (mg kg^{-1}) for both depths (**Figures 1C,D**; **Supplementary Table S6**). Olsen P stocks (0–15 cm) ranged from 9.80 to 34.7 kg ha^{-1}, with significant differences among most treatments (**Table 1**). The net change in Olsen P stocks was positive for all but the +N-P treatment and was significantly higher in the +N+P and -N+P treatments relative to other treatments (**Table 1**).

For the CW rotation, Olsen P concentrations at 0–7.5 cm were similar for all treatments in 1997, were generally greater for the -N+P treatment than other treatments from 2000 to 2009 and then were significantly greater in -N+P and +N+P than in the +N-P and -N-P treatments in 2012 and 2015 (**Figure 2A**; **Supplementary Table S7**); similar trends could be seen for Olsen P stocks (0–15 cm) and as % TP for 0–7.5 cm (**Figures 2B,C**; **Supplementary Table S7**). At 7.5–15 cm depth, Olsen P concentrations (mg kg^{-1} or % TP) were significantly higher in the -N+P treatment than the other treatments (**Table 2**). The net change in Olsen P stocks was negative for the treatments without P fertilization and positive for treatments with P fertilization (**Table 2**).

For the FW and WL rotations, Olsen P concentrations (mg kg^{-1} and % TP) were significantly higher in the +N+P treatment compared to the +N-P treatment at 0–7.5 cm but not 7.5–15 cm, and for 0–15 cm (kg ha^{-1}; **Tables 3**, **4**). The net change in Olsen P stocks was positive for both the FW and WL rotations, but was significantly different between treatments only for the WL rotation.

Crop Yields and P Depletion

There were no significant treatment*year interactions in ANOVA for grain and straw yield or grain and straw N and P for any of the studied rotations (**Supplementary Table S8**). For the FWW rotation, grain and straw yields and grain and straw N concentrations were significantly higher for the treatments receiving N (+N+P, +N-P, N only) than for the treatments without N (-N+P, -N-P, None; **Table 6**). Stopping P fertilization reduced straw P but not grain P or yields in the +N-P treatment compared to the +N+P treatment, but there were no significant differences in yield or grain and straw P for the -N-P treatment versus the –N+P) treatment. Grain and straw P concentrations were lowest in treatments not receiving P from 1967 (N only, None). There were significant differences by year for yield and grain and straw N and P concentrations, with lowest yields and concentrations in cumulative year 2003 and 2009 (**Supplementary Table S9**). These cumulative years include the years with lowest total precipitation, in 2001, 2007 and 2009 (**Supplementary Figure S1**). Both mean and cumulative P depletion (the difference between P removed in grain and P added in fertilizer) were negative for the -N+P treatment, and were positive for other treatments (**Table 1**). This indicates that less P was removed in grain than was added with fertilizers for the –N+P treatment, but not for other treatments. Both mean and cumulative P depletion were significantly higher in treatments without P (+N-P, -N-P) than for the corresponding treatments with P (+N+P, -N+P).

In the CW rotation, grain and straw yields were significantly higher in the +N+P treatment, and were lowest in the treatments without N, regardless of P fertilization (**Table 6**). Cessation of P fertilization reduced grain and straw P concentrations for the +N-P treatment compared to the +N+P treatment, but did not significantly reduce grain and straw P in the treatments without N. Similar to the FWW rotation, on a yearly basis yields were generally lower in years with low precipitation (**Supplementary Table S9**). Mean and cumulative P depletion were negative only for the -N+P treatment, and P depletion was significantly higher in the treatments in which P fertilization stopped in 1995 compared to treatments with continued P fertilization (**Table 2**).

There were no significant differences with treatment for grain and straw yield or grain and straw N and P for the FW rotation or for either wheat or lentils in the WL rotation (**Table 6**; **Supplementary Table S8**). Generally, grain and straw yields were higher in cumulative year 2012 than 2016 (**Supplementary Table S10**), again reflecting differences in precipitation among years (**Supplementary Figure S1**). For the FW rotation, both mean and cumulative P depletion were positive, and were significantly higher for the +N-P treatment than +N+P treatments (**Table 3**). For the WL rotation, mean P depletions for wheat and lentils and the cumulative P depletion were significantly higher for the +N-P treatment than the +N+P treatment, and mean P depletion was negative for the lentil +N+P treatment, but was otherwise positive (**Table 4**). Both N and P fertilizers were added for the wheat phase but only P was added for the lentil phase of the +N+P treatment; the negative P depletion with lentil indicates P was accumulating with lentil because more P was added with fertilizer than was removed with the crop.

DISCUSSION

Phosphorus Accumulation With Fertilization

For the rotations of this study, the total amount of P applied to the plots receiving P (+N+P or -N+P) decreased in the order CW (10 kg P ha^{-1} yr^{-1} annually from 1967) > WL (10 kg P ha^{-1} yr^{-1} annually from 1982 for both phases of the rotation) > FWW (10 kg P ha^{-1} yr^{-1} for two of three phases of the rotation from 1967) > FW (10 kg P ha^{-1} yr^{-1} in alternate years from 1982). From 1995 to 2015 for the FWW and CW rotations, the net changes in TP (TP Δ) and Olsen P (Olsen P Δ) were positive for both treatments with P fertilization (+N+P, -N+P). For the FW and WL treatments from 2008 to 2016, both TP Δ and Olsen P Δ were positive for the FW +N+P treatment, but only Olsen P Δ was positive for the WL +N+P treatment; TP Δ was negative for that treatment. The net changes in Org P (Org P Δ) were positive for both +N+P and -N+P in CW and FWW, but were negative for +N+P for FW and LW.

In 1995, the highest Olsen P concentrations for treatments in the CW and FWW rotations were ~30 mg kg^{-1} at 0–7.5 cm depth (**Figures 1A**, **2A**). As such, the P application rate of 10 kg P ha^{-1} yr^{-1} was within the recommended rates for spring wheat in the Brown soil zone, to replace P removed in harvested crops and to maintain soil test P concentrations (McKenzie and Middleton, 2013; Government of Saskatchewan, 2022). The positive TP Δ and Olsen P Δ stocks for the treatments with P fertilization in the FWW and CW rotations indicate that continued P applications supplied more P than was required to maintain soil test P concentrations in these soils, consistent with other studies (Cade-Menun et al., 2017). This also highlights the importance of fertilizing based on soil tests rather than at a flat annual rate, because Olsen P concentrations after 2009 indicate that soil test P concentrations are adequate for crop needs, with no agronomic or economic benefit from additional P fertilization (**Figures 1A**, **2A**).

The TP Δ and Olsen P Δ were particularly high for FWW and CW plots fertilized with P but not N (-N+P), which were the only treatments for these rotations with negative mean and cumulative P depletion, indicating net accumulation rather than depletion. Build-up of TP and Olsen P concentrations when P is applied without N was previously reported in these soils for data to 2005 (Selles et al., 2011) and world-wide, including long-term experiments applying P and or potassium but not N in England (Syers et al., 2008) and China (Khan et al., 2018). Without adequate N fertilization, crop growth is poor, which in turn reduces P uptake, leaving fertilizer P to accumulate in soils. This in turn increases the risk of P loss in runoff or erosion. While presumably most producers applying chemical fertilizers would apply both P and N at locally-recommended rates, application of manure could potentially over-supply P relative to N in a similar fashion to the results here, because the ratio of P relative to N in most manures is higher than plant requirements (Eghball et al., 2002; Khan et al., 2018).

For the +N+P treatments for all rotations, mean and cumulative P depletions were positive, which is consistent with the low or negative P balances for Saskatchewan determined by Reid and Schneider (2019). Depletion of P was calculated solely from grain removal and fertilizer inputs, which is the difference method used to determine P use efficiency (Syers et al., 2008; Selles et al., 2011; Chien et al., 2012). This method does not factor in residual or legacy P remaining in the soil from previous fertilizer applications, which clearly underestimates the P available to, and used by, plants in these soils (Selles et al., 2011; Chien et al., 2012). Indeed, the cumulative P depletions calculated for +N+P treatment for the FWW, CW and FW rotations are contrary to the positive TP Δ and Olsen P Δ for this treatment in these rotations. For the CW -N+P treatment, P depletion was negative, indicating P accumulation, which is similar to Olsen P Δ (Olsen P Δ 30.3 kg ha^{-1}; cumulative P depletion -35.6 kg ha^{-1}), both of which were much lower than TP Δ for that treatment (159.6 kg ha^{-1}). Only the +N+P treatment for the WL rotation showed a negative TP Δ concentration that was comparable to the calculated cumulative P depletion (TP Δ −25.4 kg ha^{-1}; cumulative P depletion 26.2 kg ha^{-1}), although Olsen P Δ was positive. This may be due to differences in crop uptake and removal for lentils and wheat in this rotation compared to the other wheat-only rotations, or it may reflect the shorter time period of study in that rotation compared to CW and FWW rotations; further investigation is warranted. These variations among rotations highlight the need for caution and field-scale testing when applying broad scale P balance calculations in modelling to develop policies for P management (Reid and Schneider, 2019).

Concentrations of Org P at both depths and Org P Δ were not significantly different for treatments with and without P for the FWW, CW and WL rotations. There were significant treatment*date interactions in ANOVAs for Org P for the FW rotation. However, there were no significant differences among dates for the treatment with P fertilization (+N+P) for any Org P pool. For the FWW rotation, Org P (% TP) was significantly lower in treatments with P fertilization compared to those without. This indicates that Org P concentrations in P-fertilized soils in that rotation remained steady, while soil TP and inorganic P concentrations increased from inorganic P in fertilizer; this also demonstrates that fertilizer P accumulated in soils with continued application.

It was hypothesized that concentrations of Olsen P, TP and Org P would increase with continued P fertilization for all crop rotations. Positive concentrations of TP Δ and Olsen P Δ for the FWW, CW and FW rotations and for Olsen P Δ for the WL rotation with +N+P and -N+P treatments generally support this hypothesis with respect to Olsen P and TP. However, Org P Δ was positive for FWW and CW and negative for FW and WL, indicating that it did not consistently increase with P fertilization. It was also hypothesized that Olsen P concentrations would change more with continued fertilization than TP and Org P concentrations, but Olsen P Δ stocks were lower than TP Δ and Org P Δ with continued P fertilization for all but the WL rotation. This suggests that applied P fertilizers do not remain in the labile P pool extracted with bicarbonate for Olsen P, and are instead converted into less labile pools.

Phosphorus Drawdown With Fertilizer Cessation

In the FWW rotation, Org P Δ and Olsen P Δ for 1995–2015 were positive after P cessation in 1995 (+N-P and -N-P treatments), and for plots not receiving any P fertilizer from 1967 (N only and None treatments); however, TP Δ was positive only for the -N-P treatment. In contrast, in the CW rotation, TP Δ was negative for the -N-P treatment and positive for the +N-P treatment, while Org P Δ was positive for both treatments and Olsen P Δ was negative for both treatments where P fertilization stopped (+N-P, -N-P). The mean and cumulative P depletions were positive for all FWW and CW treatments without P fertilization after 1995. For the FW and LW rotations, stopping P fertilization in 2008 (the +N-P treatment for both rotations) produced positive results for FW TP Δ, FW Org P Δ and FW and LW Olsen P Δ, but negative results for LW TP Δ and LW Org P Δ. In both the FW and WL rotations and for both lentils and wheat in the WL rotations, mean and cumulative P depletions were positive. For all rotations, mean and cumulative P depletions were significantly higher in treatments without P fertilization compared to continued P fertilization, regardless of N fertilization.

These results indicate that stopping P fertilization reduced soil TP and Olsen P compared to treatments with continued P fertilization, which is consistent with the results for P fertilizer cessation studies from other regions, including Denmark (Rubæk et al., 2013), Ireland (Cade-Menun et al., 2017), Germany (Medinski et al., 2018), Canada (Liu et al., 2019), and with a global data set (Appelhans et al., 2020). Drawdown was greater in FWW and CW treatments fertilized with N (+N-P) than without N (-N-P), where greater crop growth would have increased P uptake. This is reflected in greater grain yields and grain P for +N-P than -N-P treatments for CW and FWW. All of these results support the belief that stopping P fertilization is a simple and effective way to draw down high concentrations of soil test P and TP (Rowe et al., 2016; Withers et al., 2019). And although the current study did not measure P losses through erosion or runoff, a similar drawdown study in the neighboring province of Manitoba showed that P in runoff was reduced by P fertilizer cessation (Liu et al., 2019), suggesting that similar results would occur for the plots of this study and elsewhere on the Canadian prairies.

Two concerns for producers with P fertilizer cessation are potential yield reductions and the time required to drawdown soil P concentrations (Withers et al., 2019). For the FWW and CW rotations, no significant differences in Olsen P stocks (kg ha^{-1}; 0–15 cm) were detected by 2005 in +N-P treatments compared with +N+P plots (Selles et al., 2011), consistent with the results of the current study. However, significant differences between the +N+P and +N-P treatments were observed in TP and Olsen P stocks with additional years without P fertilization, particularly after cumulative year 2009 for both rotations (**Figures 1**, **2**). Olsen P and TP concentrations were also significantly reduced after 8 years without fertilization for the FW and LW rotations. This is comparable to Olsen P drawdown after 7 years in croplands in Manitoba, Canada (Liu et al., 2019), but was longer than for grasslands in Ireland, in which Olsen P concentrations were significantly reduced after only 5 years (Cade-Menun et al., 2017). These differences are most likely due to differences in vegetation and rainfall. With respect to yield reductions, Selles et al. (2011) reported no significant differences in yield and grain P with and without P fertilization for FWW with N fertilization up to 2005, which is consistent with the results to 2015 for the same plots. Yields and grain P concentrations were also not significantly reduced after 8 years without P fertilizers in the FW and WL rotations. In contrast to the other rotations, significant differences in yield between the +N+P and +N-P treatments for the CW treatment were observed in 2005 by Selles et al. (2011), and by 2015 in the current study. However, as noted by Selles et al. (2011) and by Liu et al. (2015) in another study on these plots, while significant differences are seen over the whole study period, on a year-by-year basis there are no significant differences in yields for many years, especially in dry years when precipitation limited crop growth regardless of fertilization (Selles et al., 2011). Summer fallow is used to conserve moisture on the Canadian prairies, which could be why yields were less affected by fertilization in the FWW rotations (Chen et al., 2021). These results suggest that P fertilizer cessation for short (5–10 years) time periods could reduce high soil P concentrations with little effect on yield as long as N fertilization is maintained (McKenzie et al., 1992; Selles et al., 2011), especially in drought years when moisture conditions will reduce plant growth.

It is clear from this study that crops in these soils can find some P to maintain growth, even for plots with no P fertilization since establishment in 1967 (the FWW N only treatment). This study only sampled soil from the surface 0–15 cm; however, plant roots can access P from deeper soil depths (Bowman and Halvorson, 1997; Selles et al., 2011). For these rotations, only grain was removed, with straw and roots left on plots after harvest. The predominant P form in this residual plant material is phosphate (Noack et al., 2016), which will be returned to the soil after decomposition of organic matter. A high proportion of the total P in these soils is organic P (48%–65% TP), which previous studies of these plots have shown to include a range of organic P compounds including inositol hexaphosphate stereoisomers (Liu et al., 2015; Chen et al., 2021). Other studies of P fertilizer cessation, including in a corn-based cropping system in Ontario, Canada (Zhang et al., 2020) have shown reductions in organic P, indicating that this is a source of phosphate to crops after fertilizer cessation. However, in the rotations of the current study, organic P as a proportion of total P was either not significantly different in plots with P fertilizer cessation (FWW, CW, WL) or was significantly higher than plots with continued P fertilization (FW rotation), suggesting that plants on these plots were not obtaining phosphate from mineralizing organic P.

Factors Affecting P Cycling in These Soils

Long-term experiments such as this make the assumption that all factors influencing nutrient use by crops remain constant in these plots, with the only changes being the N and P fertilizers added or the P fertilizer withdrawn. However, that is not the case; there will be annual variation in some factors and long-term changes in others. As the data for this study show, in rain-fed systems annual precipitation, including both drought and flooding, will significantly alter crop growth, P uptake and P cycling (McKenzie et al., 1992; Selles et al., 2011; Khan et al., 2018). There will also be variations with crop health, including crop diseases, insect and hail damage, etc., which will alter plant growth and nutrient uptake. And on the plots of this study, long-term N fertilization with NH_4NO_3, urea and/or MAP has significantly decreased soil pH, from ~ 7 in CW -N-P plots to < 6 in CW, FWW and WL +N+P plots (Li et al., 2020; Chen et al., 2021; B. Cade-Menun unpublished data). This pH change will alter soil cations, reducing exchangeable calcium and magnesium and increasing exchangeable aluminium and iron and changing the sorption and precipitation of P compounds with these cations (Liu et al., 2015; Chen et al., 2021). It will also alter the soil microbial community and the production of enzymes that mineralize organic P (Li et al., 2020; Chen et al., 2021). This could make legacy P less available to crops, increasing P deficiencies after fertilizer cessation.

CONCLUSION AND RECOMMENDATIONS

Cessation of P fertilization has been shown in many parts of the world to draw down legacy P concentrations to agronomically-optimal levels to reduce the potential for P loss, and this is supported by the results of this study. On a short-term basis this can be done with little to no effect on yields, and is best achieved when there are no other factors limiting crop growth, including deficits in moisture or other nutrients. However, the results of the current study also indicate that the rate of P draw down will vary among crops, and among different rotations of the same crop. The results of this study also show that legacy P will accumulate even with fertilization at locally recommended rates, which suggests that fertilizer guidelines may need to be revised, to minimize environmental impacts from soil P accumulation and to more efficiently use the finite rock phosphate used to produce chemical P fertilizers.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

BC-M was responsible for all aspects of this manuscript.

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CONFLICT OF INTEREST

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2022.10737/full#supplementary-material

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