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1. Project title and ADF file number.

ADF Project no. 20150077, Sask Canola Development Commission CARP 2015-077, Sask Wheat Development Commission 151106-19, Sask Pulse Crop Development AGR 1605 Crop Response to Foliar Applied Phosphorus Fertilizer

2. Name of the Principal Investigator and contact information.

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4. Abstract/ Summary: *This must include project objectives, results, and conclusions for use in publications and in the Ministry database. Maximum of 300 words in lay language.*

This study evaluated the response (agronomic, nutritional, and environmental) to foliar mono-potassium phosphate (KH_2PO_4) fertilization of canola, pea and wheat grown in Brown, Dark Brown and Black soils in Saskatchewan. In a randomized complete block design (RCBD), each P fertilization treatment plot received equivalent P fertilizer rates of 20 kg P_2O_5 ha^{-1} with varying proportion of P applied as seed-placed mono-ammonium phosphate (MAP) versus foliar KH_2PO_4. The treatments were: 1) control with no added P; 2) 20 kg P_2O_5 ha^{-1} seed placed MAP; 3) 15 kg P_2O_5 ha^{-1} seed placed and 5 kg P_2O_5 ha^{-1} foliar applied; 4) 10 kg P_2O_5 ha^{-1} and 10 kg P_2O_5 ha^{-1} as seed placed and foliar applied P; 5) No seed-placed MAP with all 20 kg P_2O_5 ha^{-1} as foliar applied P. Foliar treatments were made prior to anthesis in controlled environment studies conducted with two soils (Echo and Krydor associations), and field studies with four soils (Echo, Krydor, Sutherland and Weyburn associations) in 2016 and 2017. Of the three crops, canola was the most responsive to foliar P fertilization in terms of yield and P uptake response, followed by wheat and pea. Pea showed little response to P fertilization in general, attributed to its ability to effectively scavenge soil reserves of P. Evidence of P uptake through canola and pea leaf material was observed, but foliar P application did not effectively balance off the yield lost by reduced rates of seed-placed MAP fertilizer. Foliar P fertilization at the rates applied in this study had limited effect on human nutritional value of the grain as assessed through effect on grain Zn, Fe and phytate concentrations. Furthermore, there were no large discernible impacts of proportion of P applied in foliar versus soil applied on the dissolved reactive inorganic P (DRP) measured in simulated snowmelt runoff from post-harvest soils in controlled environment and field studies. It is concluded that mid-season foliar P applications would be most suitable for a top up of P nutrition applied in small amounts under conditions of soil P deficiency rather than a substitution for seed row applied P fertilizer. It may be most suitable for canola where P demands are high and amounts applied at seeding in the seed row may be limited by seed-row safety concerns.

5. Introduction: *Brief project background and rationale.*

The most common P fertilizer used in Saskatchewan is granular monoammonium phosphate (MAP) with common numeric designation 11-52-0, which is typically soil applied near the seed during seeding to promote early root growth, causing a *'pop-up'* effect as the crop establishes quickly and evenly (Saskatchewan Ministry of Agriculture Phosphorus in Crop Production Fact Sheet). Due to its low mobility in the soil, fertilizer P is most effectively applied in or near the seed row. However, close proximity of the P fertilizer to the seed limits the rate at which it can be applied before injury occurs due to the salt effect of the fertilizer. Crop sensitivity of different to marginally increase yield with increased grain fill (Benbella and Paulsen, 1998; Gray, 1977). In wheat, the most effective time of application is believed to be before anthesis (Mosali et al., 2006; Batten et al., 1986; Rose et al., 2007) to improve tiller production. The greatest benefits have been observed under low moisture and highly P deficient soil conditions. Previous research suggests that soil applied P at seeding supplemented with foliar P application can increase crop yield and quality (Green, and Racz, 1999; Ling and Silberbush, 2007; McBeath et al., 2011; Mosali et al., 2006). Outside of a P deficient soil, there are many environmental, biological and physiological factors affecting plant response to foliar spray: leaf age, leaf surface, leaf ontogeny, leaf homogeneity, canopy development, light, temperature, humidity, plant species and variety (Fernandez et al., 2013). Stomata have been observed to contribute to the foliar absorption process (Eichert and Burkhardt, 2001; Eichert and Goldbach, 2008). Efficacy is also dependent on the foliar solution regarding its concentration, solubility, solution pH, molecular weight, electrical charge, point of deliquescence and additional adjuvants (Fernandez et al., 2013). As Saskatchewan producers grow increasingly interested in improving agronomic efficiency, it is necessary to evaluate methods of addressing P deficiency while minimizing practices that lead to build up of soil P susceptible to export in water runoff.

Within the seed, P is primarily stored as phytic acid (PA) that accumulates in protein vacuoles located in the aleurone layer of wheat. Phytic acid (PA) comprises up to 80 % of total seed P and can comprise as much as 1.5 % of seed dry weight (Bohn et al., 2008). It is considered an anti-nutrient due to its ability to bind to minerals such as calcium (Ca), potassium (K), zinc (Zn), iron (Fe), manganese (Mn) and Mg, rendering them unavailable for human digestion and nutritional non-factors (Bohn et al., 2008). However, the impact of soil application versus foliar application of P on seed phytate content is not known. Zinc (Zn) and Fe are essential micronutrients in human health and deficiencies are a significant health concern in several human populations throughout the world. Both Zn and Fe have been found to be positively correlated to one another in terms of concentrations in the plant (Bohn et al., 2008), but Zn and P have been shown to be negatively correlated and P induced Zn deficiency has been attributed to P fertilizer application made in Zn deficient soils (Soltangheisi et al., 2014) that could be a result of a reaction or antagonism in the soil or some interference in transport of Zn from soil to shoot. High rates of P fertilizers reduce Zn translocation to the shoot (Novais et al., 2016), which may decrease concentration of Zn in the seed. On the other hand, Zn fertilizers have been found to only reduce P availability from fertilizer P sources and not soil P (Soltangheisi et al., 2014). Foliar P application that provides P directly to the shoot and leaves may address plant P deficiency without interfering with soil Zn uptake or translocation to the shoots, contributing to higher Zn bioavailability in the seed.

There has been little research on foliar P application in prairie soils. The agricultural landscape of Saskatchewan is dominated by Chernozemic soils typically associated with enriched organic matter content in the surface (A) horizon and neutral to alkaline in pH. These soils can be associated with high free lime ($CaCO_3$) content, especially in the drier regions with less leaching. Research work has been conducted outside Canada and has reported some benefits from foliar P in primarily horticultural crops and some agricultural crops. Information is needed on agronomic and environmental implications of including foliar P fertilization as an application strategy for small grains including canola, pea and wheat on the prairies. Few if any studies have evaluated the efficiency and fate of foliar applied P fertilizers under western Canadian conditions in the field. The research conducted in this project addresses this gap.

The general goal of the research was to determine the crop and soil response to foliar applied P fertilizer that is applied alone, and in combination with soil applied P.

Specific objectives were:

Determine the effect of different proportions of soil versus foliar applied P on agronomic crop (canola, wheat, and pea) response (yield, nutrient uptake and composition) and residual soil P fertility at different locations in Saskatchewan with contrasting soil and environmental conditions.

Determine the efficiency and effectiveness of the added fertilizer through assessment of recovery of the added P in the crop and soil, effects on human nutritional components including grain phytate, Zn and Fe

MAP and 10 kg P_2O_5 ha^{-1} as foliar applied P; 5) No seed placed MAP with all 20 kg P_2O_5 ha^{-1} as foliar applied P. The foliar P source used was mono potassium phosphate (KH_2PO_4) dissolved in water and with an activator adjuvant added as recommended to promote foliar absorption (Table 1. 1). Mono potassium phosphate (KH_2PO_4) was used because KH_2PO_4 fertilizer is soluble and has been used in previous studies of foliar P nutrition (e.g. Green and Racz, 1999). Any potential effect of K in the foliar treatment was assumed to be negated by high available K content of soils at the sites, with soils deemed not deficient in K according to soil test. Further, a blanket application of K fertilizer was also made to override possible influence of the treatments on K nutrition and yield. Each wheat and canola plot received a blanket application of urea (46-0-0) at 100 kg N ha^{-1} equivalent and 44 kg K_2O ha^{-1} + 17 kg S ha^{-1} as potassium sulphate (0-0-44-17). Nitrogen was not added to the pea plots and the peas were inoculated with *R. leguminosarum* commercial inoculant. Each plot also received a blanket application of Zn and copper sulphate at 5 kg Cu ha^{-1} and 5 kg Zn ha^{-1}. Application of foliar P fertilizer was made in-season for each crop at a time corresponding to when another crop protection operation (fungicide or insecticide) for which combination with the foliar fertilization would be practical for the grower. The foliar P was applied to each crop during canopy closure, as this is typically a time of high disease pressure and when there is ample opportunity for leaf interception of foliar applied P. In the pea this was the 6-9 node stage, in canola the 5-8 leaf stage before bolting, and near flag leaf emergence (Zadoks 32 - 37) for the wheat.

Table 1.1 Description of liquid foliar P treatments.

Rate	Water Volume		Concentration
kg P_2O_5 ha^{-1}	L ac^{-1}	mL $plot^{-1}$	g L^{-1}
5	43.5	13.1	115
10	43.5	13.1	230
20	87.0	26.1	230

Phosphorus source is K_2PO_4. Commercial adjuvant "Xiameter" is added at 0.125 % volume. Plot area is 0.0003 ac.

Seeding rates of pea, wheat and canola were 140, 100, and 6 kg ha^{-1} respectively with Central Butte and Mawer sites seeded in first week of May, Rosetown in the second week and Pilger in the third week of May in both 2016 and 2017. Plots were 3 m^2 with three rows in each plot of 3 m length, 25cm apart and the plots 50 cm apart. To harvest of the above- ground crop grain and straw biomass was conducted in the last two weeks of August when ripe from each plot using hand sickles, with two one meter row lengths (1 m^2) as representative plot samples to account for variability during seeding taken from each plot. Harvested plant samples were placed in cloth bags and air- dried at 30°C before analyses.

brought to volume (75 mL) with distilled water. Tubes were capped and inverted to mix the solution. The extract was analysed using atomic absorption/ flame emission spectroscopy (AA/FES) for K, microwave plasma emission spectroscopy for S, and N using the Technicon™ automated colorimeter.

Soil extractable, available P and K was measured by modified Kelowna extraction. Kelowna solution was prepared by dissolving the constituents into distilled water producing a solution with 1.4 % w/w acetic acid, 1.9 % w/w ammonium acetate, and 0.056 % w/w ammonium fluoride. A bottle containing 30 mL of Kelowna solution received 3 g of air dried soil and was placed on a rotary shaker for 5 minutes at 142 rpm. The mixed solution was filtered through VWR 454 filter paper and refrigerated at 4° C until analysed for phosphate using the Technicon™ automated colorimeter and K analysed using flame emission spectroscopy on an Agilent™ AA-Fe spectrometer.

Extractable soil nitrate and sulphate was determined using calcium chloride ($CaCl_2$) extractant prepared by dissolving 1.11 g of $CaCl_2$ in 1.0 L of distilled water. In the extraction 20 g of soil was combined with 40 mL of the $CaCl_2$ solution in an extraction bottle and placed on a rotary shaker at 142 rpm for 30 minutes. The soil suspension was then filtered through Whatman #42 filter paper into 7 dram vials. The vials are stored at 4° C until analysed for ammonium and nitrate by the Technicon™ colorimeter.

Soil extractable Zn and Fe were determined by DTPA extraction using the methods described by Lindsay and Norvell (1978). In 200 mL of deionized water, 149 g of 0.1 M triethanolamine (TEA), 19.7 g of 0.005 M Diethylenetriaminepentaacetic acid (DTPA), and 15 g of 0.01 M $CaCl_2$ were added to the water until DTPA was fully dissolved. Using 1 M HCl, solution pH was brought to 7.3, and solution was brought to 10 L volume with deionized water. Thirty grams of air dried soil was mixed with 60 mL of DTPA solution and shaken for 2 hours on rotary shaker at 142 rpm. Extract was filtered through Whatman #42 filter paper and analysed on the auto analyser. The Fe and Zn concentrations in the extract were measured using an Agilent™ atomic absorption spectrometer.

Soil electrical conductivity and pH was measured with a 2:1 water to soil solution placed on a rotary shaker at 1425 rpm for 20 minutes. The bottles are left to settle for an hour, after which the solution was filtered through Whatman #1 filter paper into 7 dram vials to be measured with a pH and EC probe.

Seed phytate content of wheat and pea samples was measured in the University of Saskatchewan Crop Development Centre Pulse Lab using the method outlined by Vaintraub and Lapteva (1988) and modified by Gao et al (2007). This method is based on use of "Wade's Reagent". Seed samples are ground and weighed into duplicates of 0.05 g and placed in a micro tube, which received 1 mL of 0.8 M HCl and shaken for 24 hours. Samples were then centrifuged at 8000 rpm for 20 minutes before transferring 10 μL of extract into a fresh micro tube. The extract received 740 mL of distilled water and 250 mL of modified Wade's reagent. From each duplicate 200 μL was transferred into a microplate cell and read in an autoanalyzer at 490 nm. The standards used were prepared with PA dodecasodium salt hydrate at concentrations of 50, 100, 200, 300, 400 μL PA dodecasodium salt hydrate per mL.

1.4 Growth Chamber Controlled Environment Studies

The reason for the growth chamber studies was to evaluate the effect of foliar P treatment under controlled conditions using soil that was taken from the control treatments of the field study described previously, and to assess P uptake in a closed system. The growth chamber study component of the research was conducted during the winter months of 2016 and 2017 in the University of Saskatchewan College of Agriculture and Bio resources phytotron facility. The study was performed using surface (0-15 cm depth) soil collected from the control (no P fertilizer added) wheat plots at each field site. It was used to evaluate crop and soil response (this section) and determine P export in run-off as affected by P fertilization treatment under controlled conditions. The growth chamber study used hard red spring wheat (var Waskada), green pea (var Sage), and Argentine canola (Invigor L252). Two different soils were used for each crop: the Central Butte SK site Echo association soil and the Pilger SK site Krydor association soil. For logistical purposes plastic potting trays were used in which each tray is separated into two equal compartments using a plastic divider that seals each compartment, and each

1.5 Statistical Data Analysis

Where applicable, means separations were performed using PROC GLIMMIX in SAS (version 9.4; SAS Institute, Cary, NC). Tukey's protected HSD was used for multi-treatment comparisons. Treatment and crop were analysed as fixed treatments with block analysed as a random effect. Outliers were determined by Grubbs Test. An alpha level of significance of 0.05 was chosen to deem a treatment effect as significant in the controlled environment experiments, while a level of 0.10 was used in the field studies. The higher alpha level in the field component was chosen to reflect the generally higher degree of variability encountered with small plot size and hand-application and harvesting of the crop samples in the field. P values are reported in ANOVA tables for main treatment effects and interactions.

1.6 Weather Data

Temperature and precipitation data for the 2016 and 2017 seasons at the sites are shown in Table 1.2 and indicate two contrasting growing seasons in southern Saskatchewan in general: wet in 2016 and dry in 2017. The 2016 Pilger location weather data shows the area received below average rainfall in the spring and early summer but above average rainfall through the middle and towards the end of the season including a wet July with almost double the previous 5 year average of rainfall. Comparatively, in 2017 the Pilger site location had above average spring moisture but below average rainfall throughout the growing season and finished with less than the average seaosnal rainfall. Pilger temperatures were similar to the previous 5 year average for 2016 and 2017. In 2016, the Central Butte site received above average rainfall for most of the growing season and finsished with 63 mm more total precipitation than the previous 5 year average. However, the 2017 season was very dry at the Central Butte and Mawer sites in south-central SK, which had dry conditions in spring that persisted throughout the growing season and finished the season with 161 mm less total rainfall than the average for the previous five years. Temperatures were slightly cooler than average in 2016 and 2017 at the Central Butte and Mawer sites. The Rosetown site location, which was used in 2016 only, received about average spring precipitation but well above average summer rainfall and in total received 162 mm more rainfall than the previous 5 year average. However, the upper slope location of the Rosetown site allowed for adequate drainage throughout the growing season, preventing long standing periods of saturation or standing water that was detrimental to crop growth and yield in the surrounding Rosetown area.

harvested that were then air-dried and placed inside insulated wooden boxes lined with plastic to funnel the leachate water into plastic buckets (Figs. 4.1, 4.2). Then addition was made of 2.0 kg (~15-cm) of snow placed on top of the soil in the boxes and the soil slab + snow allowed to melt at 20°C for 24 hours. This provided a simulation of potential for P movement in snowmelt run-off/leachate from a late fall snowfall event. Snow for the study was collected immediately after a snowfall event close to Waldheim, SK at N 50° 08.047' W 104° 36.554'. As the boxes were tilted at an 8° angle, as snowmelt occurred, the snowmelt runoff was collected over the 24 hours and the volume measured at the end. The collected run-off was filtered through a 0.45 micron filter paper to determine the DRP concentration following the method of Smith et al (2011) and King et al (2017), and analyzed for DRP colorimetrically using an automated colorimetry system (Technicon AA2 continuous flow system) based on ammonium molybdate reaction with P (Murphy and Riley 1962). The snow itself was analyzed for background P concentration and this was subtracted from the P measured in the runoff water from the slabs.

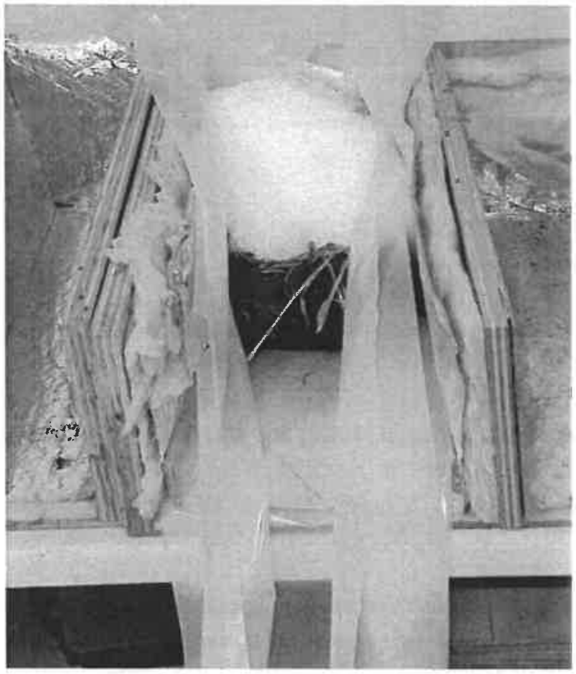

Figure 2.1: Frozen soil slab inside insulated box with melting snow on the soil surface to create snowmelt leachate.

7. Research accomplishments: *(Describe progress towards meeting objectives. Please use revised objectives if Ministry-approved revisions have been made to original objectives.)*

Objectives	**Progress**
1) To determine the crop response to foliar applied P alone and in combination with soil applied P.	Milestones and goals have been achieved. In 2016 and 2017, seven randomized complete block design small plot field experiments were set up and conducted in Saskatchewan with different combinations of soil and foliar applied phosphorus on peas, wheat and canola. As well, the growth chamber studies were completed as planned with two soils from the field trials used to evaluate response under controlled conditions. An additional field scale study with replicated strips of a commercial foliar P product was added in 2017.
2) To determine the efficiency of the applied P fertilizer in recovery and loss	Milestones and goals have been achieved. Measurements of grain and straw P content and recovery in plant and soil following application treatments have been made for all field trials and controlled environment studies. Fe, Zn and phytate have been measured in grain samples to determine influence of treatments on human nutritional value. Assessment of export of P in simulated snowmelt water from the different treatments in the controlled environment studies has been completed. In an added study, intact slabs of soil collected from field plots post-harvest at the Central Butte field research site were also used in a snowmelt run-off study to evaluate how the soil-applied and foliar P applied treatments influenced the export of P off-site in snowmelt run-off.

add additional lines as required

8. Discussion: *Provide discussion necessary to the full understanding of the results. Where applicable, results should be discussed in the context of existing knowledge and relevant literature. Detail any major concerns or project setbacks.*

1. AGRONOMIC CROP AND SOIL RESPONSE TO FOLIAR PHOSPHORUS FERTILIZATION

1.1 Site Soil Characterization

The basic soil properties including pH, electrical conductivity (EC), organic carbon (OC) and extractable available P using modified Kelowna extraction (MK-extractable P) for the research sites are shown in Table 1.3. The spring MK-P assessment indicates the Pilger sites to be the most P deficient over both years. Low intial extractable available P according to soil test should provide conditions which promote response to P treatment as long as crop demand for P is high (Al Harbi et al., 2013). This would be the case under the 2016 growing conditions in southern SK, but dry conditions in 2017 particularly at the Central Butte and Mawer sites would limit the crop demand. The highest organic carbon (~4.5%) was found in the Pilger sites over both years, consistent with the higher soil organic matter (SOM) content associated with Black soils while the lowest (1.1%) was at the Central Butte site located in the Brown soil zone. The pH values of all sites were neutral to basic ranging from 7.9 – 8.3. The Pilger location has the highest pH values which is consistent with the more calcareous nature of the soil in that region, with carbonates evident by effervesence throughout much of the profile. The innately high P fixing behavior of calcareous soil as found at the Pilger location should promote foliar P efficacy (Al Harbi et al., 2013). The electrical conductivity (EC) values were low and similar across all sites, indicating non-saline conditions. The site at Central Butte in 2016 had slightly higher E.C. than the other sites, consistent with wet conditions that spring, and the poorly drained and saline- solonetzic nature of the Echo association soils with their Bnt horizon.

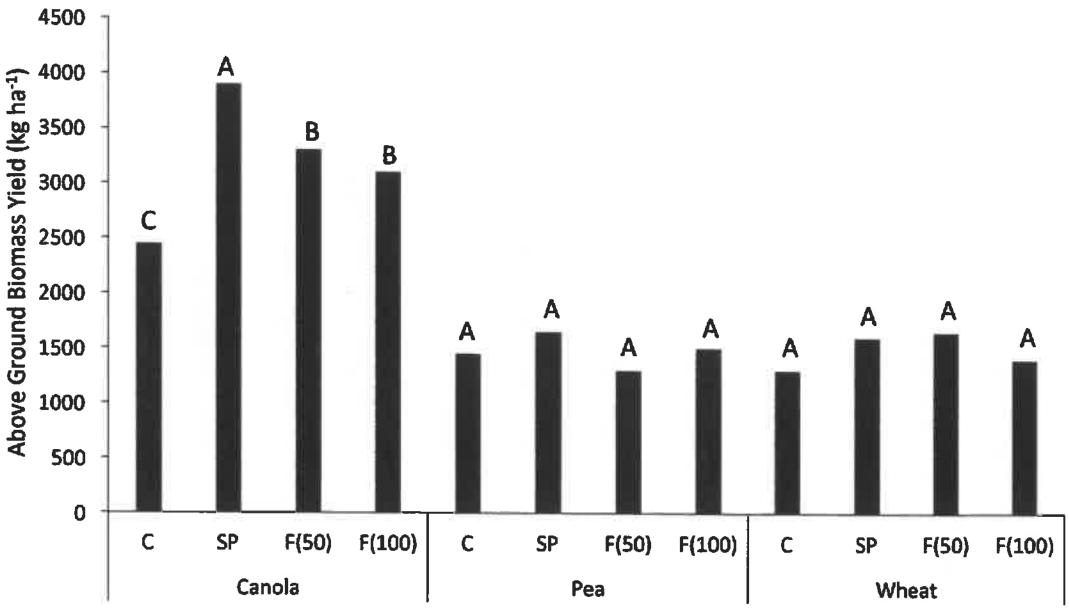

Figure 1.3: Above ground biomass yield in controlled environment trial with Krydor association soil from Pilger site. Means were separated using Tukey's protected HSD (α=0.05). Means with same letter within same crop are not significantly different. All P fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Treatments labelled C, SP, F(50), F(100) denote control, all P seed-placed, 50% P seed placed and 50% applied as foliar, and 100% P applied as foliar P, respectively.

Central Butte Site Echo Association

The controlled environment study conducted on the Echo association soil collected at the Central Butte location revealed that of the three crops evaluated, canola was the most responsive to foliar P application in total above ground biomass (grain + straw), followed by wheat and pea (Fig 3.3). Similar findings were also observed in the field at this site (see section 3.4.3.2). In canola, the SP treatment produced significantly more total above-ground biomass than the C and F(100) treatments, while the F(50) treatment was only significantly greater than the control treatment. Overall, in the canola, total biomass production decreased as the proportion of seed placed P decreased, suggesting lower uptake efficiency associated with foliar P treatment than seed placed P. No significant differences were observed amongst any treatments in pea or wheat.

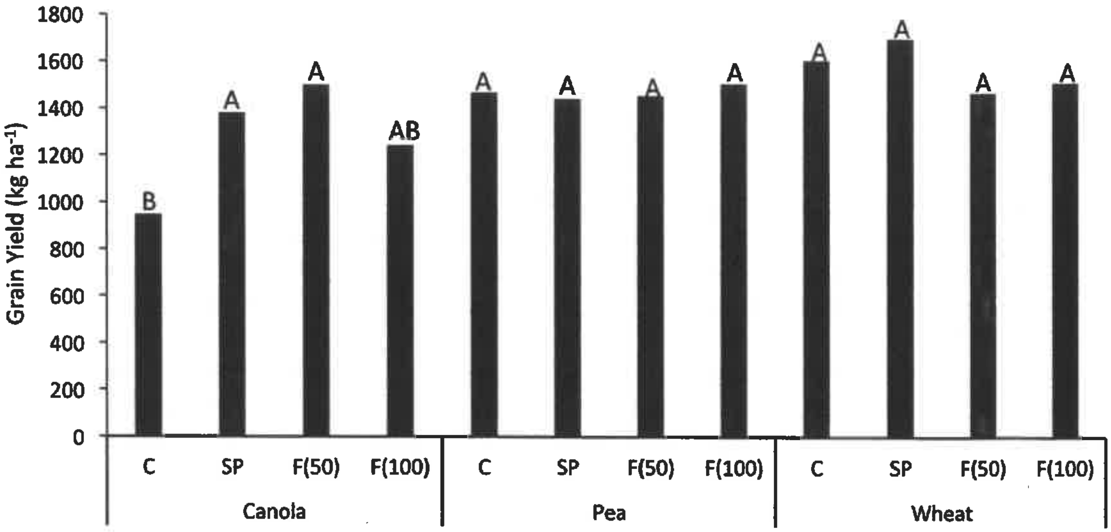

Figure 1.5: Grain yields in controlled environment trial with Echo association soil from Central Butte site. Means were separated using Tukey's protected HSD (α=0.05). Means with same letter within same crop are not significantly different. All P fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Treatments labelled C, SP, F(50), F(100) denote control, all P seed-placed, 50% P seed placed and 50% applied as foliar, and 100% P applied as foliar P, respectively.

The addition of P fertilizer at 20 kg P_2O_5 ha^{-1} to canola grown on the Echo association soil from Central Butte increased P uptake in grain and straw in all fertilizer addition treatments (Table 1.4). There was no significant difference among seed placed, foliar and the combination treatments. For peas, there was no difference among any of the treatments, including the control, in P uptake in the grain and straw, and values were all similar. The lack of response of the peas in P uptake to P fertilization follows the lack of response of the peas in yield, and can be attributed to the ability of this crop to efficiently scavenge P already present in the soil. Lack of response of pea to P fertilization has been observed in other studies in Western Canada such as Walley et al. (2005). In wheat, only grain P uptake responded to fertilization, and was highest when all the P was seed-placed followed by the F(50) treatment, pointing to greater effectiveness of the seed-placed P. Wheat straw P showed no significant response to foliar P application and neither pea grain nor straw uptake was significantly affected by P fertilization strategy. Overall, especially for pea and wheat, much of the above ground P uptake was in the grain, which was removed at harvest.

Table 1.4: Grain and straw P uptake (kg P ha^{-1}) from crops grown in Echo association soil from the Central Butte site under controlled environment conditions.

Crop	Treatment†	Straw P	Grain P
		——————kg P ha^{-1}——————	
Canola	*C*	0.71c	1.13b
	SP	1.68a	2.11a
	F(50)	1.24a	2.41a
	F(100)	1.62a	2.04a
Pea	*C*	0.89	2.23
	SP	0.98	2.53

2013).

Due to the greater surface area of the canola leaves compared to pea and wheat, greater proportions of the foliar spray that was applied could be observed to land on the leaf instead of falling in between to the soil surface. Foliar P efficacy is a function of plant P demand and leaf interception of foliar fertilizer (Pierce et al., 2014), and interception is thus a function of leaf morphology and application method (spray vs drip). A crop with many horizontally oriented, broad and cupping leaves such as canola can also be expected to have more stomata in a position to allow liquid to enter, which has been identified as a significant uptake pathway (Fernandez et al., 2005; Eichert, 1998). A photo is provided in Fig. 1.6 from this study that shows canola and wheat plants 24 hrs after foliar P application, in which KH_2PO_4 salt residue can be seen adhered to the leaves. McBeath et al., (2011) reported high stem P variability making it difficult to identify actual plant uptake and assimilation of foliar P fertilizer into the interior of the plant. Plant tissue was not washed prior to analysis in this study due to risk of loss of water soluble P from the interior of the tissue (McBeath et al., 2011). However, since the trays in the chamber were watered from the top of the tray without any water passing over the leaves, it is possible that some foliar applied P remains on the exterior of the leaf for some time. Previous research in wheat has involved application of foliar P at Zadoks stage 39 (flag leaf) (Mcbeath et al., 2011) and Zadoks 55 (ear emergence) and 65 (mid-anthesis) (Pierce et al., 2014), compared to the current study which was Zadoks 37 (flag leaf emergence) (Zadoks et al. 1974). This gives more time for absorption and redistribution. High proportions of P are redistributed and translocated to the grain during anthesis (Grant et al., 2001) and the proportion of foliar P translocated has been seen to be reduced as rate increases during very late season applications (Pierce et al., 2014). Foliar ammonium phosphate application has been observed to remedy deficiency in wheat as early as 20 – 25 days after seeding (Haloi, 1980) but is likely less effective when application is delayed. Plant response to P is a response to an increased photosynthetic capacity, producing more carbohydrates that are later translocated to the grain during senescence (Chapin and Wardlaw 1988). The potential of pre-anthesis foliar application would then be to maximize P accumulation in vegetative growth while those cells are importing nutrients before they become source cells. It would appear that there may be a fairly wide window of response to foliar P in wheat, with greater P demand and translocation associated with anthesis (Grant et al., 2001; Benbella and Paulsen, 1998; Pierce et al., 2014; Mcbeath et al., 2011) that also might suggest later season application of foliar P to be more appropriate. However, recovery of applied P can further be reduced by senescence (Pierce et al., 2014) and translocation to roots (McBeath et al., 2011).

(see Table 1.3) and relatively good growing conditions that year. Overall, across the sites, 2016 generally had better growing season moisture (see Table 1.2) than 2017, where drought limited yield, especially for canola and pea in the southern Saskatchewan sites located at Central Butte and Mawer (Table 1.6). Some issues with pests in specific crops occasionally arose such as cutworm injury in wheat at the Pilger site in 2016, and some bird damage to wheat and pea at the Mawer site in 2017. Responses are discussed on a site by site basis in the following sections.

Table 1.5: P values for treatment effect on grain yield, straw yield, and grain and straw P uptake using Tukey's protected HSD for fixed effect in the P fertilization field trials conducted in 2016 and 2017 (α=0.10).

Site (Association)	Effect	Numerator df	Variable†							
			Straw Yield		Grain Yield		Straw P		Grain P	
			2016	2017	2016	2017	2016	2017	2016	2017
Pilger (Krydor)	Crop	2	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	**0.0051**	<.0001
	Treatment	4	**0.0007**	0.1982	<.0001	0.1566	0.9417	**0.0581**	**0.0005**	0.2516
	Crop*Treatment	8	**0.0008**	0.7634	<.0001	0.2988	0.2927	0.696	**0.001**	0.3514
Central Butte (Echo)	Crop	2	<.0001	<.0001	**0.0515**	<.0001	<.0001	<.0001	<.0001	<.0001
	Treatment	4	**0.0675**	0.824	0.5955	0.9784	0.8502	0.6357	0.76	0.8933
	Crop*Treatment	8	**0.0407**	0.538	**0.0557**	0.5323	**0.07**	0.7966	0.2927	0.4474
Rosetown (Sutherland)	Crop	2	<.0001	*NT*	<.0001	*NT*	<.0001	*NT*	<.0001	*NT*
	Treatment	4	0.1036	*NT*	0.9619	*NT*	0.5239	*NT*	0.9232	*NT*
	Crop*Treatment	8	**0.0017**	*NT*	0.3883	*NT*	0.392	*NT*	0.701	*NT*
Mawer (Weyburn)	Crop	2	*NT*	<.0001	*NT*	<.0001	*NT*	<.0001	*NT*	<.0001
	Treatment	4	*NT*	0.488	*NT*	0.7607	*NT*	0.1239	*NT*	0.3902
	Crop*Treatment	8	*NT*	**0.0584**	*NT*	0.5609	*NT*	**0.0011**	*NT*	0.1688

† Variables containing NT indicate no trial was conducted at that site that year. Bolded values are significant at p<0.10.

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Means were separated using Tukey's HSD. Means with same letter within same crop, site, column and year are not significantly different (α=0.10) and no letters denotes no significant differences.
‡ NT denotes no trial was conducted at that site that year.

Pilger Site Krydor Association

The Pilger site soils used in the study had the lowest P fertility according to soil test (Table 1.3), consistent with rates of P fertilizer application made by the grower over the years that were much less than crop removal. Comparing the 2016 grain and straw yield as well as P uptake at the Pilger site (Table 3.6), of the three crops evaluated (canola, pea, and wheat) canola (P<.0001) was the most responsive to treatment as it displayed significant differences among all parameters except 2017 straw yield. This is consistent with results from the controlled environment studies (see section 3.3) in which the Pilger site Krydor association soil was also most responsive. For canola grain yield, the seed-placed P (SP) treatment produced significantly (p<0.10) greater yield than all other treatments followed by the F(25), F(50) and F(100) treatments respectively, which were significantly greater than the control (C) treatment. Higher proportions of P fertilizer applied with the seed appeared to favor higher canola yield and P uptake in both 2016 and 2017. Grain P uptake was greatest in canola in the SP treatment which was significantly greater than all other treatments. Overall, canola had the highest grain P content followed by pea, with wheat the lowest. Straw yield and P uptake followed a similar pattern to grain yield. For all crops, the majority of the above-ground P content was found to reside in the grain. Annual crops have most of their above ground P content (>70%) in grain at maturity (Havlin et al., 2014).

Pea grain yield at Pilger responded positively to P fertilization only in 2017 and, like canola, only when all the P was seed-placed. The response diminished when some or all of the P was foliar applied. In 2016, there was no positive grain yield response of pea to P fertilization and the lowest pea yield, lower than the unfertilized control, was observed in the 100% foliar P treatment. This suggests that some injury to pea may have occurred when all 20 kg P_2O_5 ha^{-1} was applied as foliar spray. The setback in yield observed by the F(100) treatment could be caused by foliar burn as a result of increased salt-load on the leaf (Pierce et al., 2014). However, we did not observe any marked foliar injury symptoms on the peas when the site was visited one week after application, although symptoms may have manifested and disappeared during the week between time of application and time of sampling. Correlations between severe leaf burn and reduced yields have been reported (Parker and Boswell 1980), but others have found burn symptoms to have no association with crop yield (McBeath et al. 2011; Phillips and Mullins 2004). Foliar burn can be induced by dissolved fertilizer applied in low water volumes over a small leaf surface area that produces injury from increasing acidity (pH <2) and/or salt concentrations (Pierce et al., 2014). Pea is also a relatively effective scavenger for soil P and, as such was expected to be less responsive to added P fertilizer treatment in general due to acidification of the rhizosphere and the strong mycorrhizal relationships they develop, enhancing their ability to access native soil P and reducing their requirement for added P fertilizer (Hinsinger, 2001). This may explain the lack of difference between the control and SP treatment in which fertilizer application had no significant effect on yield.

Wheat yield and P uptake was not significantly affected by treatment at the Pilger site both years, which may be attributed to some significant cutworm pressure on this crop. However, wheat showed a pattern in yield and P uptake response to P fertilization treatment that was similar to that observed with canola and pea: higher proportion of P in seed-placed form favored yield and above-ground crop P content.

	F(100)	2465	2108ab	(-)357a	2684	1945b	(-)740
	C	.	2414a	.	.	1765b	.
Wheat	F(25)	3178a	2916	(-)263	2582	2107	(-)475
	F(50)	2517b	2721	(-)204	2511	2224	(-)287
	F(100)	2460b	2424	(-)36	2557	2131	(-)426
	C	.	2426	.	.	1972	.

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Means with same letter within same crop within same column are not significantly different and no letters indicates no significant difference (α=0.10).

Central Butte Site Echo Association

In 2016, the Central Butte site Echo association soil showed significant treatment effect on yield and crop in straw and grain P uptake and straw and grain yield, depending on crop (Tables 3.5 and 3.6). At this site, canola in 2016 appeared to show a slight reduction in grain yield with greater proportion of P applied with the seed, as the treatments F(25) and SP were the lowest yielding but only F(25) was significantly lower than the control treatment (Table 1.6). For canola straw yield the F(25) and F(100) treatments resulted in significantly less straw biomass production than the C and F(50) treatments. The reduction in yield observed in 2016 with the seed placed P may reflect some injury, as conditions were relatively dry in early May immediately after seeding that produced patchy germination and emergence early on. However, rains later in May and throughout the season at this site in 2016 contributed to compensation and overall very good canola yields (3000-4500 kg ha^{-1}) in the end. In 2017, canola yields were greatly impacted by dry conditions later in the growing season, with grain yields <1000 kg ha^{-1} at this site. The 2017 canola grain yield results showed the F(25) treatment to produce the greatest grain yield but it was only significantly greater than the F(100) treatment. There were no positive significant responses of canola yield to P fertilization at the Central Butte site in either 2016 or 2017, reflecting sufficient supplies of soil P at this site which are consistent with its history of use of moderate rates of applied P (~20 kg P_2O_5 ha^{-1}) annually, and relatively low crop removal over the years due to generally moisture limited conditions. Canola P uptake followed similar trends to grain yield, with significantly higher grain P uptake in 2017 in the F(25) treatment than the other treatments. This suggests that under the dry 2017 growing conditions at this site, 15 kg P_2O_5 ha^{-1} with the seed and a top-up with 5 kg P_2O_5 ha^{-1} as foliar applied P resulted in best plant P utilization of the 20 kg P_2O_5 ha^{-1} rate. This provides some support to the concept of foliar P being more beneficial under adverse growing conditions such as dry soil that may limit P movement by diffusion and also root growth.

The effects of P fertilization on pea yields and plant P uptake in grain and straw at this site were small and the only significant treatment effects were observed in the 2017 straw pea straw. The pea straw P was greatest in the C, F(100) and F(50) treatments and which were significantly greater than the SP treatment. Foliar application appeared to increase straw P in this crop and little else, as the peas showed no response to treatment among the remaining variables in 2016 or 2017. Lack of significant response is consistent with the higher P fertility at the Central Butte location compared to Pilger, and ability of legumes to effectively scavenge and use P that is already present in the soil.

Wheat grain and straw yields in 2016 (Table 1.6) were greatest in the SP and F(50) treatments which were significantly greater than the C and F(100) treatments, indicating better performance when some P is applied with the seed at seeding. Foliar P application did not significantly affect grain P uptake but was higher when some of the P was applied with the seed at the time of seeding. For straw P uptake, the SP treatment resulted in the greatest straw P uptake that was significantly greater than the control treatment. In 2017 P fertilizer application

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Means with same letter within same crop and column are not significantly different and no letters indicates no significant difference (α=0.10).

Rosetown Site Sutherland Association

In the Rosetown site field trial, conducted in the 2016 growing season on soil mapped as Sutherland association, canola was the only crop that showed significant response to the P fertilization treatments, with a significant crop by treatment interaction (Table 1.5 and Table 1.6) for straw yield. A significant response in canola was observed in grain and straw yield as well as grain and straw P uptake to treatment. For grain yield, the C and F(50) treatments produced the greatest yield, which were only significantly greater than the SP treatment, which had the lowest yield. A similar trend to yield was observed in the canola P uptake. The lack of positive response to P fertilization and the depression of yield and P uptake in the seed-placed P treatment in the canola is explained by the history of P application at recommended rates by the grower (~ 20 to 30 kg P_2O_5 ha^{-1}) and use of no-till over a number of years at this site, resulting in good soil P fertility. Uneven germination and emergence was observed with the seed-placed P treatment in canola at this site, similar to the Central Butte site due to dry conditions in early spring, which may have contributed to reduced yield. Under these conditions, a reduced proportion of P applied as seed-placed and an increased proportion in foliar form appeared to be of benefit for the canola. At the Rosetown site, there was no significant response of pea or wheat to P fertilization treatment (Table 3.6), with similar yields and P uptake among all treatments. The yield and uptake results from the Rosetown sites do not indicate additional uptake of soil or foliar applied fertilizer P under conditions of high soil P availability. Growing conditions during the season at Rosetown were considered good but the available P in the Sutherland association soil was not likely deficient enough to elicit a response to foliar P. This is consistent with other research that indicates growth promoting environmental conditions that increase crop P demand along with soil P deficiency conditions are contributors to increasing foliar P fertilizer efficacy (Al Harbi et al., 2013; Silberbush, 2002).

The mid-season above ground canola plant tissue P concentrations at the Rosetown site (Table 1.9) were not significantly different among treatments, but there were significant differences in the change in concentration, suggesting an increase in plant P arising from the foliar application in the canola. This effect was also observed in wheat, with effects more variable in the pea. Therefore there is some evidence for foliar P at least residing on the surface of the leaf following application, if not taken up into the interior of the plant. However, given the similarity and lack of any significant effect on straw or grain content at harvest in the treatments compared to the unfertilized control, the foliar applied P may have simply washed off over the season. If P had been translocating to the roots at time of application, a surplus of P binding sites in the leaf may have been present, increasing the absorption potential of the leaf surface (Fernandez et al., 2009). In wheat and canola it would appear that some uptake occurred through leaf tissue but there was no notable change in agronomic factors to discern foliar P fertilizer as having equal or greater efficacy than seed placed MAP.

Table 1.9: 2016 Rosetown field site mid-season above ground plant tissue P concentration pre- and post-foliar P application treatment and the change (Δ) in tissue P concentration.

Crop	Treatment†	Pre-App	Post-App	Δ
		————————	mg kg^{-1}	————————
Canola	F(25)	4837	3812	(-)1025b
	F(50)	4584	3724	(-)860ab

conditions in early July at flowering and pod formation likely contributed to the low pea grain yields observed relative to straw production. Wheat yields were low and similar among all treatments at this site. The wheat and pea also suffered some damage from blackbird flocks. Across all crops at the Mawer 2017 site, the high rate foliar P treatment (F(100)) resulted in the greatest grain P uptake but was only significantly greater than the SP treatment. Significant positive response was measured in canola (p=0.0114) and pea (p=0.0005) straw P content at the Mawer 2017 site.

The mid-season plant tissue P concentrations in Table 1.10 show no significant differences in P concentration amongst treatments until after foliar P treatment (Post-App). At this site in 2017, the sampling was delayed by about six days compared to the other sites, explaining the lower concentrations of plant material as a result of further growth dilution. Across canola, pea and wheat, all tissue concentrations decreased between sampling periods. For canola and pea, foliar P application generally increased the P concentration measured in collected plant tissue, while, interestingly, in wheat it appeared to result in a decrease. Overall, foliar P application had little effect on P content among all three crops nor did a trend consistently favor foliar or seed-placed P fertilizer. Lack of significant results may be due to limited uptake caused by dry weather or rapid uptake and mobilization of applied P fertilizer to somewhere else (e.g. roots) that occurred between sampling periods (Barrier and Loomis, 1957; Bouma, 1969).

Table 1.10: 2017 Mawer field site mid-season above ground plant tissue P concentration pre- and post-foliar P application treatment and the change (Δ) in tissue P concentration.

Crop	Treatment†	Pre-App	Post-App	Δ
		———mg kg^{-1}———		
Canola	F(25)	2245	1637b	(-)608
	F(50)	2165	1889a	(-)276
	F(100)	2257	1737ab	(-)520
	C	.	1768ab	.
Pea	F(25)	1594	1375a	(-)219
	F(50)	1745	1254ab	(-)492
	F(100)	1518	1356a	(-)161
	C	.	1052b	.
Wheat	F(25)	1671	1161ab	(-)457
	F(50)	1689	1000b	(-)690
	F(100)	1801	1247a	(-)554
	C	.	1373a	.

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Means with same letter within same crop within same column are not significantly different and no letters indicates no significant difference (α=0.10).

Growth in 2017 was inhibited in large part by below-average spring and summer precipitation in southern Saskatchewan which would inhibit overall nutrient demand and uptake and potentially the capacity of crops to respond to P treatment. Drought reduces photosynthesis and therefore P demand, furthermore plants respond to drought with various mechanisms such as stomatal closure and increased diffusive resistance (Farooq et al., 2012). It might be anticipated that the foliar P spray applied would have less efficacy under these conditions as stomatal closure would potentially make movement into the leaf more difficult. However, the concentration of a nutrient in a foliar spray will always be significantly higher than found within plant organs and a concentration gradient will

Table 1.11: 2016 and 2017 foliar P field trial P values for treatment effect on grain Zn and Fe concentration using Tukey's protected HSD for fixed effect in Pilger site foliar P field trial in 2017 (α=0.10).

Site	Effect	Numerator df	Variable†			
			Zn		Fe	
			2016	2017	2016	2017
Pilger	Crop	2	**<.0001**	**0.0685**	**0.0218**	**<.0001**
	Treatment	4	**<.0001**	0.3626	**0.0203**	0.2101
	Crop*Treatment	8	0.2742	**0.0846**	**0.0033**	0.2546
Rosetown	Crop	2	**<.0001**	*NT*	**0.0015**	*NT*
	Treatment	4	0.9712	*NT*	0.3117	*NT*
	Crop*Treatment	8	0.2814	*NT*	0.103	*NT*
Central Butte	Crop	2	**<.0001**	0.3521	**<.0001**	**0.0311**
	Treatment	4	0.6656	0.6045	0.1084	0.5529
	Crop*Treatment	8	**0.0196**	**0.0148**	0.7484	0.6489
Mawer	Crop	2	*NT*	0.2652	*NT*	**<.0001**
	Treatment	4	*NT*	0.1960	*NT*	0.3567
	Crop*Treatment	8	*NT*	0.7235	*NT*	0.1608

† Variables containing NT indicate no trial was conducted at that site that year. Bolded values are significant at p<0.10.

As noted, at the 2016 Pilger site, canola grain Zn concentration was greatest in the C, F(50) and F(100) treatments which was significantly greater than the SP treatment (α=0.10) (Table 3.12). Although this effect may be explained largely by growth dilution, there may also be an antagonistic interaction between Zn uptake and soil applied P which has been reported in previous research (Ryan et al., 2008; Lu et al., 2011; Zhang et al., 2012). The trend in Fe concentration suggests that foliar P is beneficial to Fe concentration, but this may only be a consequence of a lower yield response when more P is added in foliar form. The Pilger 2016 site pea grain Zn concentration was also greatest in the unfertilized control which was significantly greater than the SP and F(25) treatments, indicating the same interaction between soil P and Zn uptake appearing to have occurred in pea as in canola. Foliar P application did not significantly affect pea Zn or Fe concentration, consistent with limited effect of P treatment on yield. Overall, application of P fertilizer, especially when all or a high proportion is applied in the seed-row at the time of seeding, results in lower concentration of the nutritional elements Zn and Fe in the grain. This impact is largely attributed to yield response and growth dilution from the added P, but may also reflect some antagonism between high levels of soil P and uptake of Zn by the plant as observed in previous research.

Zn (Erdal et al., 2002). It can be difficult to establish a clear relationship between fertilizer P treatment and phytate content as in the current study when the same rate of P is applied but in different form, time and placement, though positive linear correlation between PA content and P fertilization rate in pea has been observed (Marzo et al., 1997). Higher soil P levels prior to P fertilization might account for elevated phytate in pea and wheat in this study compared to others (Barr and Ulrich, 1963; Batten et al., 1986; Chapin and Bieleski, 1982; Lee et al., 1976). High concentrations of orthophosphate in non-seed tissue has been seen to stimulate phytate production (Mitsuhashi et al., 2005), but application of P mid-season to the foliage may be less effective than P that is available and taken up early on in the growth cycle as when P is seed placed at the time of seeding. Other research, however, has found relative proportions of P species in grain were unaffected by plant P status in canola and wheat crops, with deficient, adequate, or luxury P status resulting in different concentrations of total P but the proportion of this P present as orthophosphate versus phytate varied little (Noack et al., 2014). Furthermore, the predominant P species returned to the soil in crop residue was orthophosphate followed by phytate (Noack et al., 2014). While foliar P fertilizer generally had little effect on seed phytate levels in this study, elevated P levels in straw as a result of foliar P fertilization may be returned to the soil as phytate or orthophosphate. In general, based on the results of this study it appears that foliar P fertilization may be expected to have no effect, or possibly a small positive effect on human bioavailability of micronutrient metals in pea and wheat grain. However, as the proportion of foliar P applied becomes high, a yield penalty may occur when grown under P deficient conditions.

Table 1.13: Combined analysis of 2016 and 2017 field site pea and wheat grain phytate concentrations measured using Wade's reagent phytate concentration results.

Treatment†	Pea	Wheat
	——mg phytate g^{-1}——	
C	10.5	16.1
SP	11.1	17.7
F(25)	10.9	15.8
F(50)	9.9	14.8
F(100)	10.9	14.8

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Means were separated using Tukey's HSD. Means with same letter within same crop, site, nutrient and year are not significantly different (α=0.10) and no letters denotes no significant differences.

1.5.4 Fall Soil Available Phosphorus Indices

Fertilization strategy had relatively little effect on the soil residual available P (Table 1.14). This general trend is expected as the same rate of P fertilizer (20 kg P_2O_5 ha^{-1}) was applied in all treatments but with different proportions of soil vs foliar applied. However, there were some significant differences. Phosphorus (P) fertilization generally increased the level of residual available P compared to the unfertilized control, as expected. However, the effects were not consistent among site, crop, treatment, year or method. Effects of canopy interception, retention in straw and residue along with differences in plant and microbial uptake and removal in precipitation all likely contributed to differences observed. Although some significant differences are observed among the P

Table 1.14: Available P indices in soil (0-15cm) collected post- harvest from P fertilization trials in fall 2016 and 2017.

Extraction	Site	Crop	Treatment†									
			C	SP	F(25)	F(50)	F(100)	C	SP	F(25)	F(50)	F(100)
			2016					2017				
Water Extractable (kg P ha^{-1})	Pilger	Canola	3.0	3.0	3.2	2.9	3.3	4.0	3.7	3.9	4.2	3.8
		Pea	2.9ab	2.4b	3.4a	2.6b	2.7ab	3.8b	4.8ab	4.2b	5.7a	4.4b
		Wheat	2.8	3.2	3.1	3.1	2.8	3.4	3.8	3.2	4.1	3.7
	Central Butte	Canola	1.1	1.6	0.6	1.3	1.3	5.0b	7.4ab	6.2b	9.3a	6.0b
		Pea	1.8	1.8	2.1	2.2	2.4	4.7	5.1	5.2	4.7	4.3
		Wheat	2.2	2.2	2.2	2.5	2.3	4.3ab	5.4ab	5.0ab	6.8a	3.9b
	Rosetown	Canola	5.3	4.2	4.8	6.8	3.9	NT	NT	NT	NT	NT
		Pea	2.8	3.9	9.1	4.2	6.6	NT	NT	NT	NT	NT
		Wheat	7.7	7.4	8.7	6.1	5.1	NT	NT	NT	NT	NT
	Mawer	Canola	NT‡	NT	NT	NT	NT	1.7b	3.3a	2.3ab	1.5b	2.0b
		Pea	NT	NT	NT	NT	NT	1.7b	3.7a	2.2b	2.1b	2.1b
		Wheat	NT	NT	NT	NT	NT	2.0	2.2	2.3	2.4	1.8
MK-P(kg ha^{-1})	Pilger	Canola	15.1	15.8	15.5	14.6	14.2	9.7	8.5	7.2	11.1	9.7
		Pea	11.6b	14.4a	13.2ab	15.4a	13.2ab	8.7b	8.2b	18.8a	10.1b	9.4b
	Central Butte	Wheat	11.8	14.3	12.6	13.2	12.2	8.3	9.3	8.9	11.8	10.5
		Canola	8.7b	10.8a	9.0b	9.6ab	10.9a	13.1b	22.7a	14.7b	23.8a	17.4ab
		Pea	8.2	8.7	8.1	9.3	8.0	14.1	16.1	12.2	16.3	13.3
	Rosetown	Wheat	7.7b	9.2ab	10.3a	9.9a	9.0ab	NT	NT	NT	NT	NT
		Canola	22.4	19.8	24.0	29.1	20.4	NT	NT	NT	NT	NT
		Pea	17.0	21.1	29.1	19.0	23.6	NT	NT	NT	NT	NT
	Mawer	Wheat	NT	NT	NT	NT	NT	14.4ab	16.8ab	15.1ab	19.9a	12.2b
		Canola	NT	NT	NT	NT	NT	5.6	8.4	8.2	7.9	6.0
		Pea	NT	NT	NT	NT	NT	6.3b	10.9a	8.1ab	6.6b	6.2b
Membrane Exchangeable P ($\mu g\ cm^{-2}$)	Pilger	Wheat	25.5	31.9	31.0	22.9	20.7	8.3	9.1	8.3	10.3	6.4
		Canola	0.1a	0.1a	0.0b	0.1a	0.1ab	0.2	0.2	0.3	0.3	0.2
		Pea	0.1	0.1	0.1	0.1	0.1	0.2b	0.3b	0.5a	0.4ab	0.3b
	Central Butte	Wheat	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.2	0.3	0.2
		Canola	0.1	0.2	0.2	0.2	0.2	0.5b	0.7ab	0.6b	0.9a	0.5b
		Pea	0.1	0.1	0.1	0.1	0.1	0.4	0.6	0.4	0.5	0.4
		Wheat	0.1	0.1	0.1	0.1	0.1	0.3b	0.5ab	0.4b	0.7a	0.3b
	Rosetown	Canola	0.2	0.2	0.3	0.3	0.2	NT	NT	NT	NT	NT
		Pea	0.2b	0.3b	0.6a	0.3ab	0.4ab	NT	NT	NT	NT	NT
		Wheat	0.3	0.5	0.5	0.4	0.3	NT	NT	NT	NT	NT
	Mawer	Canola	NT	NT	NT	NT	NT	0.1b	0.3a	0.2ab	0.2ab	0.1b
		Pea	NT	NT	NT	NT	NT	0.1b	0.3a	0.2ab	0.1b	0.1b
		Wheat	NT	NT	NT	NT	NT	0.1	0.2	0.1	0.2	0.1

Treatment	Wheat kg/ha Total Biomass	Wheat kg/ha Grain Yield
Foliar P-humate	7767	2975
Control	7770	2872

	Std Dev. kg/ha Total Biomass	Std Dev. kg/ha Grain Yield
Foliar P-humate	234	253
Control	302	198

The concentrations of P, Zn and Fe in the P crop at maturity were generally higher in lower slope positions (Table 1.16), reflecting greater soil nutrient availability in low slopes. There were few significant treatment effects on plant P concentrations, but occasionally in pea the foliar P-humate treatments resulted in slightly but significantly lower concentration compared to the untreated control, while in canola the treatment generally resulted in higher concentration, while in wheat the effects were variable. The low amounts of P and Zn directly supplied in the foliar spray at the recommended rate of 2 l per acre (e.g. 0.2 kg P_2O_5 ha^{-1}) explain the lack of impact on plant concentrations, although the humate component may affect concentration through possible effects on translocation and growth stimulation.

Table 1.16. Straw and grain P concentration and total Zn and Fe concentration in the grain in P-humate foliar spray 2017 farm field trial.

PEA *Treatment*	Slope Position	Straw P		Grain P		Total Zn		Total Fe	
		ug g^{-1}							
Foliar P-humate	UPPER	233.7	a[†]	2803.9	a	39.1	a	78.1	a
	MID	249.8	b	3320.2	b	30.8	a	90.0	a
	LOWER	265.2	b	3505.3	a	42.5	a	76.9	a
Control	UPPER	241.7	a	3184.8	a	20.9	a	70.0	a
	MID	270.5	a	3890.4	a	38.9	a	72.2	a
	LOWER	347.1	a	4139.6	a	49.8	a	82.0	a
Upper Slope $LSD_{(0.10)}$		60.5		1482.1		47.2		43.3	
Mid Slope $LSD_{(0.10)}$		12.4		321.8		9.7		63.8	
Lower Slope $LSD_{(0.10)}$		78.2		910.2		8.9		7.9	

[†]Means followed by the same letter are not significantly different at $p \leq 0.10$ for the same slope position

2. SUSCEPTIBILITY OF FOLIAR VERSUS SOIL APPLIED PHOSPHORUS TO EXPORT IN SIMULATED SNOWMELT RUNOFF AND LEACHATE

2.1 Foliar P Controlled Environment Trial

The p values from the snowmelt runoff-leachate collected from controlled environment studies (Table 2.1) indicate no significant crop, P treatment or crop by treatment effect in the Central Butte soil, but do show significant effects for all three factors in the Pilger soil. This continues the trend of the low soil available P Pilger site as being generally the most responsive site to treatment in this study. These findings agree with the results of Weiseth (2015) and Wiens (2018). In their comparisons of MAP fertilizer placement on P removed in snowmelt runoff-leachate, only the low P fertility soil used by Weiseth (2015) showed a significant effect of MAP placement method on export in simulated snowmelt. In the current study, the crops that showed significant responses to soil versus foliar P fertilization treatment were wheat and pea while canola ($p = 0.1203$) did not.

Table 2.1: P values for treatment effect on DRP concentrations in simulated snowmelt runoff and leachate using Tukey's protected HSD for fixed effects in soil versus foliar P applied P controlled environment studies using Central Butte and Pilger site soil.

Site Soil	Effect	Numerator df	P Runoff-Leachate
Central Butte	Crop	2	0.2533
	Treatment	3	0.1146
	Crop*Treatment	6	0.5322
Pilger	Crop	2	**0.0002**
	Treatment	3	**0.0079**
	Crop*Treatment	6	**<.0001**

Bolded values are significant at p<0.10. Bolded values are significant at p<0.10.

The DRP concentrations in the post- harvest controlled environment run-off - leachate from the Central Butte site soil (Fig. 2.4) ranged from 0.004 mg P L^{-1} to 0.084 mg P L^{-1}. The greatest DRP levels were measured in the wheat F(50) treatment, which was significantly greater than the C and F(100) treatments. No significant differences were observed among foliar P treatments in pea or canola, although concentrations of P in runoff-leachate from the soil on which pea was grown was generally higher. This may reflect higher content of soluble P in remaing pea straw and roots after harvest compared to the other two crops.

The snowmelt DRP concentrations from the Pilger soil (Fig. 4.5) were of a slightly wider range, from 0.002 mg P L^{-1} to 0.11 mg P L^{-1}, compared to the Central Butte soil. The greatest DRP concentration in the post-harvest snowmelt runoff and leachate was found in the Pilger soil wheat F(100) treatment which was signficantly greater than all other wheat treatments. This follows a trend similar to that observed in the Central Butte soil, where P concentrations in snowmelt overall tended to be higher in wheat and pea stubble than in canola. This may be a consequence of greater P uptake by the canola, leaving less P behind in the soil, roots and surface residue. Differences in leaf architecture may also contribute to differences observed, with the broader, flatter orientation of the canola leaves resulting in greater interception of the foliar P spray (Fernandez et al., 2013). The SP treatment had the highest DRP concentrations in the run-off and leachate from the trays with peas, which was significantly greater than all other treatments, while F(50) treatment was significantly higher than the C and F(100) treatments in canola. In both sites, the greatest DRP levels were measured in wheat while the lowest were in canola.

Overall, application of P fertilizer tended to increase DRP concentration in runoff and leachate collected

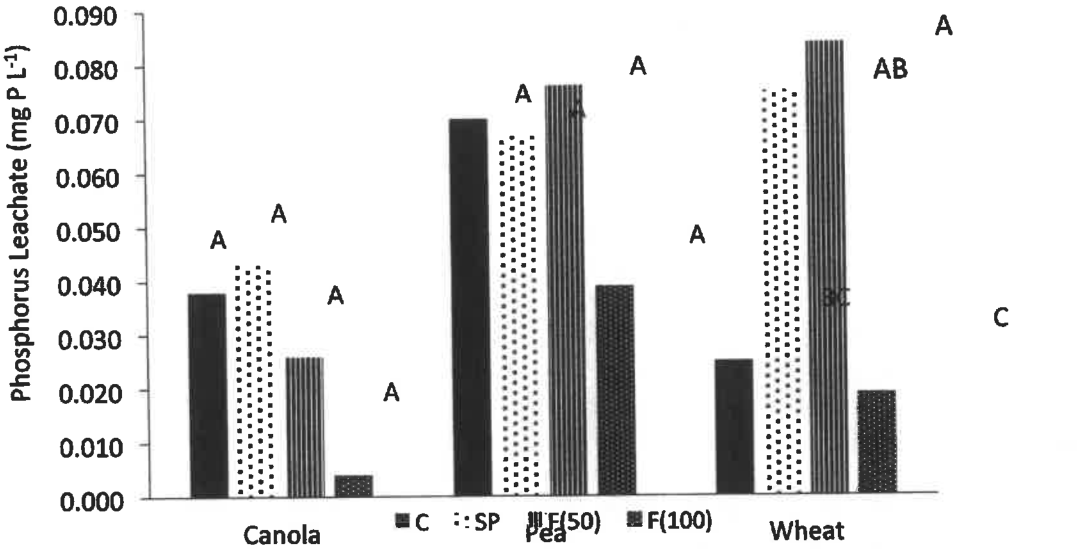

Figure 2.4: Simulated snowmelt runoff - leachate DRP concentrations (mg P L^{-1}) from Central Butte site soil in controlled environment study. Treatments labelled C, SP, F(50), F(100) denote unfertilized control, all P (100%) seed placed, 50% P applied as foliar and 50% as seed placed, and 100% P applied as foliar respectively, at a rate of 20 kg P_2O_5 ha^{-1}. Total leached P means were separated using Tukey's HSD. Means with same letter within a crop are not significantly different (α=0.10).

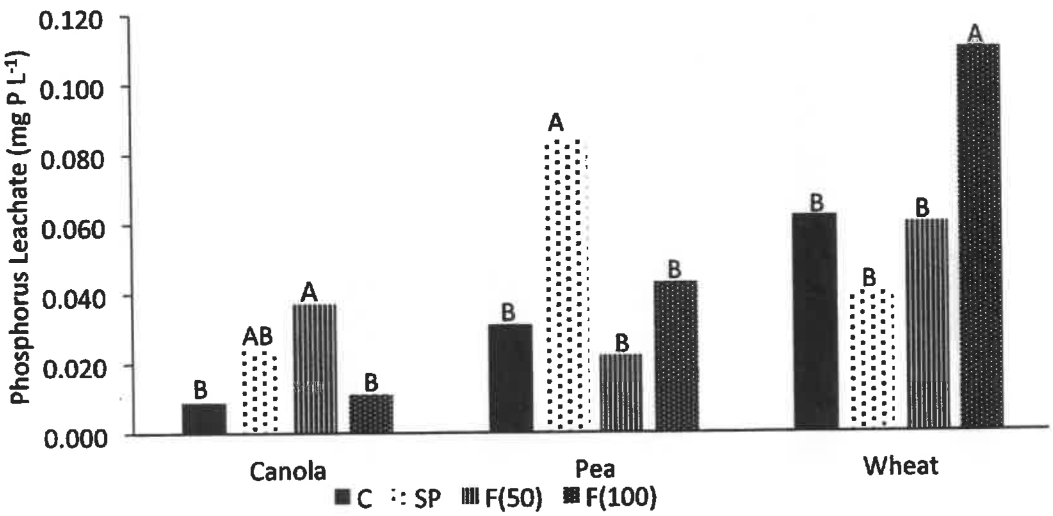

Figure 2.5: Simulated snowmelt runoff - leachate DRP concentrations (mg P L^{-1}) from Pilger site soil in controlled environment study. Treatments labelled C, SP, F(50), F(100) denote unfertilized control, all (100%) P seed placed, 50% P applied as foliar and 50% as seed-placed, and 100% P applied as foliar respectively, at a rate of 20 kg P_2O_5 ha^{-1}. Total leached P means were separated using Tukey's HSD. Means with same letter within a crop are not significantly different (α=0.10).

2.2 Foliar P Field Trial

leachate values observed in this study were below the threshold concentration for total P for a healthy water body on the Canadian Prairies reported to be 0.26 mg P L^{-1} (Glozier et al., 2006). Overall under the parameters set in this study, application of P in foliar form versus seed-placed, or a combination thereof, did not have a consistent positive or negative effect on P export in snowmelt runoff and leaching that was independent of crop or soil type. With the exception of wheat grown on the Pilger soil under controlled environment conditions, P fertilization in which some or all MAP was applied in the seed-row resulted in higher concentrations of DRP in the snowmelt runoff-leachate than foliar application. While P fertilizer application in general tended to increase DRP concentrations, high crop interception and uptake appears to be associated with reduced P loss in snowmelt run-off and leachate. Effect of runoff passing specifically through loose chaff and senesced leaf material was not evaluated in the controlled environment studies, which may be more significant contributors to P leaching.

9. Conclusions and Recommendations: *Highlight significant conclusions based on the previous sections, with emphasis on the project objectives specified above. Provide recommendations for the application and adoption of the project.*

Of the crops evaluated in this study, canola was the most responsive to foliar P fertilization with pea the least. Increased P tissue concentrations and P uptake observed after foliar treatment in the absence of seed placed MAP indicates that some uptake of foliar P occurred in canola. While uptake did occur, it was not associated with consistent, significant positive yield and P uptake responses. In this study, soil P arising from pre-existing pools and/or from MAP fertilizer addition at seeding, was a greater contributor to plant growth than foliar applied P, as response per increment of foliar P was less than for MAP addition. Significantly higher wheat grain and biomass yields have been reported in previous research with foliar application in addition to recommended rates of soil applied P fertilizer (Samad et al., 2014), and low rates of foliar P (~2 kg P ha^{-1}) have been stated to increase P use efficiency (Mosali et al., 2006). Foliar P is most effectively absorbed by plants when intercepting leaf area is high, and this may explain the greater responsiveness of canola observed in the current study. As well, cereal crops such as wheat require P early in the season (sowing) to promote root growth and tillering and are noted to be particularly responsive to starter seed placed P (Noack et al., 2010). Crop stage is likely to have been a factor in the current study as P demand prior to anthesis when the foliar application was made may have been less notable P export levels would be far higher than the necessary amount to achieve maximum foliar uptake. It is important to consider subsequent effects of foliar fertilization that weren't analyzed in this study. There was a trend for increased proportion of P applied in foliar form to result in reduced residual concentrations of labile P in the top 15cm of soil after harvest that might be attributed to P that is immobilized in organic form in the surface thatch, as noted by Wiens (2015) for broadcast P. Even under low uptake conditions, foliar P fertilizer could potentially contribute to future soil P fertility, in which case foliar P applied during the same time as a herbicide or fungicide application is both available for plant uptake (as needed) with the rest -depending on management practices- returned to the soil.

Maximizing uptake efficiency of foliar P fertilizer and indeed showing response to foliar P fertilization can be difficult, as demonstrated in the results of this study. It appears to require the simultaneous combination of rather severe soil P deficiency, high crop P demand, and growth promoting environmental conditions. This is further complicated by the limited quantity of P that is able to be absorbed by leaves as well a limited window of leaf uptake activity and the influence of environmental conditions like moisture stress, limiting the rate of foliar P which can be effectively applied. In soils with relatively good inherent P fertility that have been managed well, such as the Rosetown site Sutherland association soil, reducing or omitting P fertilizer may be the best management practice both financially and environmentally as a means to reduce excess soil P (Wiens, 2017). This study only evaluated KH_2PO_4 as a foliar P source. There are others like ammonium polyphosphate and humic-phosphate products available to growers. The humate-P product evaluated in the farm field scale trial appeared to perform in a similar manner to the potassium phosphate solution in the small plot and controlled environment studies, with best performance on canola and no response observed on the peas. More research is needed to evaluate the potential of different foliar P fertilizer compounds along with different adjuvants, as well as fertilizer blends in addition to evaluating application timing among different crops before blanket recommendations can be made. In this study, foliar KH_2PO_4 fertilization was a poor substitute for seed-placed MAP, which could a result in an absence of early season crop 'pop-up' effect, otherwise seen with seed-placed P fertilizers in small grains production on the prairies. Considering the degree of uptake that is able to occur, there is greater potential for foliar P as a top-up or supplemental fertilizer treatment to go along with seed-placed P as opposed to a substitute. The challenge is balancing crop P demand and timely application of foliar P to maximise both uptake and efficiency. Foliar P fertilization may be relatively ineffective for oilseeds, cereals and pulses in dryland agriculture compared to vegetable, nut or fruit crops grown under irrigation (Noack et al., 2010). The results of this study suggest overall uptake of foliar P fertilizer by plant leaves wasn't high enough to make a notable impact on the parameters evaluated in this study on an annual basis. These results underline the importance of the right rate, source, time and placement regarding P fertilization of canola, wheat and pea in contrasting Saskatchewan soils.

crops.

15. Acknowledgements. *Include actions taken to acknowledge support by the Ministry of Agriculture and the Canada-Saskatchewan Growing Forward 2 bilateral agreement.*

Acknowledgement to funding agencies at end of presentations and publications. Signs at field trial research sites.

16. Appendices: *Include any additional materials supporting the previous sections, e.g. detailed data tables, maps, graphs, specifications, literature cited*

Table A1: Spring pre-seed soil characterization for pH, EC, and MK-extractable P at 15-30 and 30-60cm soil depths at the field trial sites.

Year	Site	Association	Depth (cm)	Extractable P (kg ha^{-1})†	pH	EC	%OC
2016	Pilger	Krydor	15-30	17	7.9	2.7	3.8
			30-60	.	.	.	.
	Central Butte	Echo	15-30	13	8.0	0.2	0.9
			30-60	.	.	.	.
	Rosetown	Sutherland	15-30	16	8.2	0.2	1.6
			30-60	.	.	.	.
	St Brieux	Flooded out 2016	15-30	9	8.1	0.2	1.1
			30-60	.	.	.	.
2017	Central Butte	Echo	15-30	25	8.2	0.2	1.5
			30-60	20	8.3	0.2	1.2
	Pilger	Krydor	15-30	36	8.4	0.3	2.4
			30-60	59	8.4	0.3	2.4
	Mawer	Weyburn	15-30	16	8.1	0.2	0.9
			30-60	23	8.2	0.2	1.0

† Extractable P was measured using modified Kelowna (MK) method.

Table A2: 2016 spring pre-seed soil characterization for membrane exchangeable P.

Site	Depth (cm)	µg cm^{-2}
Pilger	0-15	0.03
	15-30	0.00
Central Butte	0-15	0.19
	15-30	0.12
Rosetown	0-15	0.60
	15-30	0.03
St. Brieux	0-15	0.37
	15-30	0.06

		Crop*Treatment	**0.0160**	0.1473
	Rosetown	Crop	**<.0001**	**<.0001**
		Treatment	0.9254	0.9649
		Crop*Treatment	0.4190	0.8146
2017	Pilger	Crop	**<.0001**	**<.0001**
		Treatment	0.6386	0.2535
		Crop*Treatment	0.6886	0.2653
	Central Butte	Crop	**<.0001**	**<.0001**
		Treatment	0.3092	0.9949
		Crop*Treatment	0.2369	0.3886
	Mawer	Crop	**<.0001**	**<.0001**
		Treatment	0.1498	0.5594
		Crop*Treatment	**0.0050**	0.5628

Table A7: Fall soil nitrate analysis of 2016 and 2017 foliar P field sites.

Crop	Depth (cm)	Treatment	NO_3 (kg N ha^{-1})						
			Pilger 2016	Central Butte 2016	Rosetown 2016	St. Brieux 2016	Pilger 2017	Central Butte 2017	Mawer 2017
Canola	0-15	C	12.5	6.6	9.1	x	12.7	10.6	5.4
		SP	14.5	6.4	7.1	x	7.5	33.4	5.2
		F(25)	10.8	5.2	4.8	x	7.4	10.5	2.2
		F(50)	11.3	5.8	6.8	x	8.6	9.8	3.8
		F(100)	12.2	6.3	7.9	x	17.9	14.4	4.1
	15-60	C	5	3.5	3.9	x	4.8	1.9	4.2
		SP	5.3	3.4	4.7	x	4.1	1.6	2.7
		F(25)	3.6	3.8	3.1	x	3.3	1.5	10.4
		F(50)	4.9	3.9	3.7	x	3.6	1.5	2.5
		F(100)	5.6	3.4	4.0	x	4.0	1.8	3.3
Pea	0-15	C	9.4	7.0	17.0	x	7.2	9.0	8.6
		SP	7.9	10.1	21.6	x	5.2	10.5	10.9
		F(25)	8.9	7.6	15.3	x	6.9	14.0	8.2
		F(50)	11.4	6.7	15.7	x	5.8	9.9	11.4
		F(100)	8.8	8.5	9.1	x	5.9	11.8	6.3
	15-60	C	4.7	3.5	3.9	x	3.2	2.1	2.5
		SP	3.3	4.6	4.9	x	3.9	1.7	2.9
		F(25)	3.3	3.6	4.2	x	2.6	2.1	2.1
		F(50)	4.9	3.9	4.2	x	2.4	1.9	2.6
		F(100)	4.8	3.7	3.5	x	2.3	2.2	2.4
Wheat	0-15	C	12.6	9.8	8.3	16.7	8.2	26.9	14.3
		SP	10.7	10.3	8.1	12.5	10.3	15.2	21.6
		F(25)	13.7	7.0	9.7	14.0	10.9	20.7	18.0
		F(50)	11.1	7.5	7.9	19.6	8.7	27.8	13.4
		F(100)	8.9	7.8	9.0	18.8	12.9	11.1	31.7
	15-60	C	4.5	10.1	4.6	6.9	2.1	4.2	9.9
		SP	5.5	4.2	3.2	5.3	2.7	1.5	23.0
		F(25)	4.8	3.5	3.9	7.0	4.0	2.8	4.9
		F(50)	4.0	3.3	2.8	8.2	2.9	3.4	2.8
		F(100)	4.1	5.4	3.2	8.1	1.9	3.9	22.4

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