Phosphorus Management Practices for Soybean Production in Manitoba

by

Gustavo R. Bardella

A Thesis
Submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

ABSTRACT

The increase in soybean production in Manitoba has raised many questions about phosphorus management for achieving high yields of modern varieties. Soybean's tolerance to seed-placed fertilizer and response to added fertilizer P were evaluated in a 28 site-year study, and the yield response to soil test P concentrations was evaluated in seven site-years, in a second study. Plant stand reduction caused by fertilizer toxicity when applied with the seed was rare, but was most likely in soils with medium to coarse texture or when seeding equipment lightly disturbed the soil, or provided little seed bed utilization. Severe plant stand reduction decreased seed yield in two site-years. Seed yield increase to P fertilization was rarely observed, regardless of fertilizer P rate, P placement or soil test P. In only one site-year there was a significant effect of fertilizer rate, where 45 and 90 kg P_2O_5 ha^{-1} increased yield by approximately 15%, compared to the control. Regardless of soil test P, seed yield response to soil P fertility was never observed.

ACKNOWLEDGEMENTS

I do not have words to express how thankful I am for being able to work with these great people that I met here in Manitoba. First, I would like to thank our partners in this project, including the research and diversification centres for conducting the majority of the trials and providing us with accurate and reliable data, and the companies who provided us with products or service. These partners were the Westman Agricultural Diversification Organization (Scott Chalmers), Parkland Crop Diversification Foundation (Jeff Kostuik, Angel Melnychenko, Susan McEachern), Canada-Manitoba Crop Diversification Centre (Craig Linde and Curtis Cavers), Prairies East Sustainable Agriculture Initiative (Roger Burak and Jordan Pawluk), Agriculture and Agri-Food Canada (Cynthia Grant and Ramona Mohr), Kelburn Farm (Brian Hellegards), Oak Ridge Holdings Farm (Christian Autsema), Manitoba Agriculture, Food and Rural Development (John Heard and Dennis Lange), Agvise Laboratories, BASF and Monsanto – Dekalb. Also, thank you to the Manitoba Pulse and Soybean Growers association, Western Grains Research Foundation and Manitoba-Canada Growing Forward 2 Program for generously funding this project.

I really appreciated the technical and staff support of the departments of Soil Science and Plant Science, especially Tim Stem, Lynda Closson, Alvin Iverson and Dr Lawley's research group. Also, I want to thank the support of Dr. Francis Zvomuya with

the statistical analyses. I could not forget of my colleagues, graduate students, for the great time working together and for all the help exchanged. I want to say a special thank you to Magda Rogalsky for all the help, patience and for being a good friend, who made my time in Canada very precious.

My advisory committee was delightful and brilliant. I could not have better people in this team. I am privileged for officially being oriented by Dr. Don Flaten, Dr. Mario Tenuta and Dr. Yvonne Lawley, and also for closely working with John Heard. I am thankful for having John Heard as a teacher, an advisor, a friend and my Canadian dad! I will never forget all you have done for me, and the great moments lived together. Dr. Don Flaten is the giant that I am riding on his shoulder. My sincere thanks for your dedication and passion in teaching and advising, and for your generosity in sharing your knowledge and always willing to make us better people. I am very lucky and blessed for having you as my advisor.

Thank you to the helpers, Matheus Cassalho and Megan Bourns, who were always efficient and cared as much as me about my project. Thank you to my loved family who always stimulated and supported my studies, in special to my aunt Antonia Grequi (in memoriam). I am very proud for being part of this united family. And finally, thank you to my girlfriend, Julia, for always patiently listening to my complaints and motivating me during the moments of stress.

FOREWORD

This thesis is composed of an introduction (Chapter 1) to the topic addressed in the two studies reported in detail, in chapters 2 and 3, followed by an overall synthesis (chapter 4) and the appendices. Chapter 2 contains a manuscript for the first study, which will present the findings about the effects of phosphorus fertilizer rate and placement on plant stand, biomass, seed yield and seed quality, composed of 28 site-years of data collected in Manitoba, in collaboration with the provincial crop diversification centres at Portage la Prairie, Carberry, Melita, Roblin, Arborg and Beausejour, Agriculture and Agri-Food Canada (Brandon), Kelburn farm (St. Adolphe), and the University of Manitoba (Carman and Roseisle). This study was led by Dr. Don Flaten, John Heard and me. My role was to provide the cooperators with the necessary material for the establishment of each trial, such as fertilizer, seed and inoculant, and also assist with soil and biomass sampling, harvesting and post-harvesting samples processing, analyses and reporting. I was responsible for fully conducting the trials located at Carman and Roseisle. The third chapter is composed of a manuscript about the second study, which reports the effects of soil phosphorus fertility on soybean seed yield and P uptake. However, analyses of soil, mid-season biomass, harvesting biomass and seed are still ongoing by Agriculture and Agri-Food Canada and therefore, only the results for seed yield are presented in this chapter. Seven site-years were set up in Brandon, Forrest and Carman, using the remaining plots of a long term study, previously established in 2002. This study was led by Dr. Don Flaten and Dr. Cynthia

Grant. My role was to provide the seed and inoculant to the Agriculture and Agri-Food Canada Research Centre at Brandon, for the establishment of trials at Brandon and Forrest, support with samples processing and also to fully conduct the trial located at Carman.

This thesis was prepared according to the thesis preparation guidelines elaborated and approved in 2014 by the Department of Soil Science at the University of Manitoba. The chapters two and three were also prepared in accordance with the Canadian Journal of Soil Science guidelines since we intend to submit the manuscripts for publication in this specific journal.

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1. INTRODUCTION

Canada is ranked as the sixth largest soybean (*Glycine max* (L.) Merr) producer in the world with 5,086,400 metric tonnes produced in 2012 (Food and Agriculture Organization 2016). In this context, Canada produced in 2015, 6,235,000 metric tonnes of which 22.3% was produced in Manitoba. From 2007 to 2015, the soybean seeded areas in Manitoba increased by 5.4 fold, from 87,045 to 560,729 hectares (Statistics Canada 2016). The soybean provincial average yield in 2015 was approximately 2576 kg ha^{-1} (Manitoba Agricultural Services Corporation 2016). The rapid expansion of soybean in southern Manitoba was promoted by the low cost of production for soybean, compared to other crops, and the small heat unit requirement of the short growing season varieties.

Coincidently, with the expansion in soybean areas in Manitoba, more areas have declining soil phosphorus (P) levels, such as those reported by the International Plant Nutrition Institute (IPNI) (2016), which estimated that 64% of the soil samples analyzed for P in Manitoba tested below the critical concentration levels of soil P, seven percent more than the value of 57% estimated in 2010 (Fixen et al. 2010). Agvise Laboratories (2015) also reported declining soil P levels in Manitoba where the production of soybean is concentrated.

Phosphorus is a major nutrient of plants, taken up by diffusion as $H_2PO_4^-$ and HPO_4^{2-} (Pierzynski et al. 2005). Phosphorus is important for plant functions and plays a role in cell energy transfer, respiration and photosynthesis. Phosphate bonds are used for energy storage as adenosine triphosphate (ATP), which is the primary source of energy for biological processes, and also serve as structural component of nucleic acids (DNA and RNA), enzymes, phosphoproteins and phospholipids (Marschner 1986; Grant et al. 2001). Therefore, phosphorus deficiency can drastically affect plant development and metabolism, which can irreversibly reduce yield potential when occurring at early plant growth stages (Grant et al. 2001).

Soybean removes large amounts of P; approximately 6.2 kg of P per tonne of seed harvested (Manitoba Agriculture Food and Rural Development (MAFRD) 2007). In addition to the P removal by soybean, the large removal of P by other crops has also led to declines in soil P concentrations. For instance, the typical rates of P fertilization for high yields of current varieties of canola and wheat are often not high enough to replace crop P removal.

Manitoba's acreages of cereals such as oats (*Avena sativa*), barley (*Hordeum vulgare*) and winter wheat (*Triticum aestivum*) had reductions of 54, 61 and 50%, respectively, during the same period of soybean expansion areas previously reported, from 2007 to 2015 (Statistics Canada 2016). The major implication of this transition in seeded crops is the fact that these crops remove less P from the soil than soybean and also receive application of P fertilizer when seeded, which in the past helped to prevent or reduce soil P declines. Fertilizer application to soybean is not currently a common practice in Manitoba. Biological nitrogen fixation provides most of the nitrogen required for crop growth and P fertilizer is usually not applied because producers do not observe yield response to added fertilizer.

A typical practice of phosphorus fertilization in Manitoba is placing the fertilizer with the seed at the time of planting the crop. However, there are limitations for this practice since some crops do not tolerate high rates of seed-placed fertilizer and can have plant stand reductions caused by fertilizer toxicity. For this reason, the current provincial recommendations are maximums of 56 kg P_2O_5 ha^{-1} applied with the seeds of cereals, such as wheat, and 11 and 22 kg P_2O_5 ha^{-1} seed-placed for soybean and canola, respectively, which are crops more sensitive to fertilizer toxicity (MAFRD 2007).

Fertilizer salt content often affects seedling emergence due to the change in the soil solution's osmotic pressure, which is increased in the zone of fertilizer application restricting water supply to seed germination and seedling emergence. The concentration of salts in each fertilizer is variable and can be estimated by the fertilizer salt index, which is determined by the change in osmotic pressure when a fertilizer is applied to water, relative to the osmotic pressure of sodium nitrate applied to water (Rader et al. 1943). The higher the salt index, the greater is the chance of fertilizer toxicity to crop establishment.

High rates of fertilizer or highly concentrated placement of fertilizer because of seeding equipment with low seed bed utilization have the greatest probability to cause toxicity (Clapp and Small 1970). For instance, a rate of 20 kg P_2O_5 ha^{-1} seed-placed in 30 cm row spacings will have double the concentration when the same 20 kg P_2O_5 ha^{-1} is applied in 60 cm row spacings. Soil disturbance also plays an important role for mixing the fertilizer with the soil, reducing the concentration of the fertilizer close to the seeds. Disc openers of seeders usually cause less soil disturbance and place the fertilizer in a narrow strip, resulting in higher toxicity than the knife or sweep opener, which spreads and mixes the fertilizer, seeds and soil into the application zone (Chaudhuri 2001). Changes in osmotic pressure can also be alleviated or aggravated by soil texture. Medium to coarse-textured soils are most likely to have low water content and have less capacity to dilute the fertilizer salts. Rader et al. (1943) observed that changes in osmotic pressure are more intense in medium to coarse texture soils than in clay soils. Nevertheless, soil moisture and precipitation are variable from year to year and can dictate whether or not toxicity will occur and how severe it will be.

Even though excessive seed-placed phosphorus fertilizer can be detrimental to crop establishment, small rates applied with the seeds are often beneficial to early crop development. Starter fertilizer, which is the fertilizer applied in small rates, at the time of planting, and in close proximity to the seed (Sims and Kleinman 2005), is especially important for early shoot and root growth when, in the spring, soils are cold and plant metabolism is slow. Therefore, crops seeded in cold soils are likely to respond to starter P when seed reserves are not enough to supply early crop demand. Furthermore, P deficiency in early season may compromise yield potential even when crop deficiency is overcome later in the crop cycle (Grant et al. 2001). Touchton and Rickerl (1986) observed soybean yield response to 20 kg P ha^{-1} applied as a starter fertilizer regardless of the background soil test P in Alabama, USA. Conversely, Gervais (2009) conducted phosphorus fertilization trials in Manitoba and did not find yield response to P regardless of rate and placement. Lauzon and Miller (2008) suggested that soybean has large seed reserves of P, thus being self-sufficient to supply early season P requirement. Moreover, soybean is generally seeded when soil temperature reaches 10° C, when P diffusion and plant development is not severely retarded.

Research conducted in North America on phosphorus nutrition has obtained infrequent and inconsistent responses of soybean yield and biomass to increased rates and placements of P fertilizer (Bureau et al. 1952; Florence 2015; Gervais 2009; Lauzon and Miller 2008; Mallarino 2009; Mallarino and Dodd 2005; Slaton 2009). Gervais (2009) evaluated the soybean response to six rates of P fertilizer and found no seed yield increase in five site-years of field trials in Manitoba.

Previous research on soybean fertilization with P in Manitoba has generated contradictory results about fertilizer placement. Bullen et al. (1983) observed significant yield increase to side-banded P, placed 2.5 cm below the seed or 2.5 cm below and 2.5 cm beside the seed, when compared to seed-placed or broadcast fertilizer. However, recent work comparing placement did not find any soybean yield increment obtained from P fertilizer side-banded or seed-placed (Gervais 2009). Borges and Mallarino (2000) also did not observe soybean yield response to fertilizer placement, when comparing side-band, deep-band and broadcast of P fertilizer application in 31 site-years of experiments in Iowa.

The lack of yield increase to P fertilization in combination with the high rate of P uptake and removal by soybean indicates that soybean may prefer to take up P from soil P reservoirs rather than fertilizer P. Kalra and Soper (1968) observed that P uptake from phosphorus fertilizer by soybean, rape, oats and flax in Manitoba were very similar. However, phosphorus uptake from soil reservoirs was substantially greater for soybean than for the other crops studied.

In some crops, a combination of phosphorus fertilization and good soil P fertility may be the key for reaching high yields. For instance, in a study by Wagar et al. (1985), wheat yield was maximized by a combination of broadcast P fertilizer application in order to raise the background level of P in soil, plus an annual application of seed-placed P. In this study, the single applications of broadcast or seed-placed P also increased grain yield, compared to the control, but those increases were smaller than the yield increase obtained with the combined fertilization.

Several similar studies have shown that soybean grown on high P fertility soils can produce greater yields. Randall (2012) observed greater soybean yield (2762 kg ha^{-1}) for the unfertilized treatments at high soil test P than at low soil test P (1751 kg ha^{-1}). A study conducted in Ontario had similar results, where soybean did not increase yield with added P fertilizer but had greater yields to the increased soil test P in one of the two years of the study (Lauzon and Miller 2008). Conversely, Blackmer et al. (1992) observed yield increase by P fertilization on soils with low test P. However, there was no yield response to high soil P levels. In this same study, significant yield response to fertilizer was observed at the maximum of 11 kg P ha^{-1} at the sites with high soil test P, which indicates that in soils with high P fertility, a starter P rate may be enough to increase soybean yield (Blackmer et al. 1992).

Seed quality parameters such as 1000 seed weight, and seed oil and protein concentration can be affected by phosphorus management. Furthermore, protein and oil concentrations may have an inverse relationship; the increase of one may decrease the concentration of the other and vice versa (Mallarino and Haq 2005). However, many studies have shown inconsistent seed quality responses to P fertilizer rate and placement (Gervais 2009; Fernandez et al. 2012).

Nevertheless, with the soybean area expanding in Manitoba, concerns and questions regarding phosphorus management were raised, increasing the need for local research on this topic. Proper fertilization is important to assure satisfactory crop establishment and high yield of modern cultivars, preventing declines of soil P levels and environmental losses. Therefore, in the current study, field experiments were conducted to determine the maximum safe rate of seed-placed P fertilizer for soybean, the seed yield and seed quality response to fertilizer P placement and rate, and also the optimum soil test P level for seed yield maximization, in Manitoba.

2. RESPONSE OF SOYBEAN TO PHOSPHORUS FERTILIZATION IN MANITOBA

Keywords: soybean (*Glycine max* (L.) Merr), phosphorus, plant stand, rate, placement, seed-placed

2.1. Abstract

Soybean production in Manitoba has increased substantially over the last decade, raising many questions about phosphorus fertilization. From 2013 to 2015, 28 site-years of field trials were established across Manitoba to assess soybean's tolerance to seed-placed fertilizer as well as dry matter and seed yield response to P fertilizer rate and placement. Treatments were 22.5, 45, and 90 kg P_2O_5 ha^{-1} applied as monoammonium phosphate, seed-placed, side-banded or broadcast, plus an unfertilized control treatment. Plant stand reduction was observed at five of 28 site-years, caused by seed-placed fertilizer toxicity, typically at the rate of 90 kg P_2O_5 ha^{-1}. Stand reduction was most likely to occur on medium to coarse textured soils, dry soils or when seeding equipment had low seed bed utilization. Seed yield was reduced at two site-years as a consequence of the severe plant stand reduction induced by 90 kg P_2O_5 ha^{-1} seed-placed, which reduced plant stands below 247,000 plants per hectare. Phosphorus fertilization did not increase biomass or seed yield, regardless of P rate, P placement or

soil test P level, except for one site-year where 45 and 90 kg P_2O_5 ha^{-1} increased seed yield by 343 and 430 kg ha^{-1}, respectively. Plant tissue and seed P concentration were often increased by P fertilization, but had no nutritional benefit on seed yield and quality.

2.2. Introduction

Soybean (*Glycine max* (L.) Merr) seeded area in Manitoba significantly increased during the last decade. From 2007 to 2015 the area seeded to soybean increased 5.4 fold, from 87,045 to 560,729 hectares. During this same period, the area seeded with cereal crops such as oats (*Avena sativa*) and barley (*Hordeum vulgare L)* decreased by 54 and 61%, respectively (Statistics Canada 2016).

The transition of cropped area from cereals to soybean may be one of the reasons why soil phosphorus levels are declining in Manitoba. In 2015, 64% of Manitoba's soil samples tested for P were below the critical levels for sufficiency, seven percent more than the previous value estimated in 2010 (Fixen et al. 2010; IPNI 2016). Unlike cereal crops, soybean typically does not receive P fertilization, creating a negative soil P balance. Soybean removes large amounts of P from the soil; approximately 6.2 kg of P is removed per tonne of seed harvested (Manitoba Agriculture Food and Rural Development (MAFRD) 2007). With the inadequate replacement of P removed during seed harvesting of soybean, soil test P can decline into the low range of P sufficiency in the soil.

Other factors may also contribute to soil P levels declining, including the increasingly high yields of other crops such as canola. Typical phosphorus fertilizer rates are often insufficient to replace P removed by current varieties, despite the fact that P fertilizer is being applied to these crops.

With the transition of cereals acreage to soybean, the seeding equipment was kept similar, which is characterized by solid seeding (widths between rows of 30 cm or less), often without the capacity to place fertilizer separately from the seed (i.e., without capacity to side-band or mid-row band). Part of the reason for this is that producers in this region apply the fertilizer within the seedrow for cereal crops, to maximize the starter fertilizer benefit. However, soybean is more sensitive than cereals to seed-placed fertilizer and may have reduced seedling emergence caused by the fertilizer toxicity (Gelderman 2007).

Phosphorus fertilizer, such as monoammonium phosphate (MAP), applied with seed can be toxic due to its salt content, which increases the osmotic pressure, inhibiting water supply for seed germination and seedling development. As a result, the current guideline in Manitoba for seed-placed P fertilizer recommends a maximum of 11 kg P_2O_5 ha^{-1} for soybean seeded in row spacings narrower than 30 cm (MAFRD 2007).

Some factors related to the fertilizer toxicity include the fertilizer salt index, fertilizer rate, soil moisture, soil texture, row spacing, seeder opener type and the crop’s susceptibility to fertilizer toxicity (Gelderman 2007). Each fertilizer type has a different salt index, which is a measure of the change in osmotic potential when the fertilizer is applied to water, in relation to the osmotic potential of sodium nitrate when applied to water (Rader et al. 1943). The higher the salt index, the greater are the chances of salt toxicity from the fertilizer.

Another factor affecting the risk of toxicity is the high concentration of fertilizer in or near the seedrow. These high concentrations can be caused by high rates of fertilizer application and/or wide row spacings. For instance, a rate of 30 kg P_2O_5 ha^{-1} applied with the seed in 20 cm row spacing will have the fertilizer concentration doubled if applied in 10 cm row spacing.

The width of spreading of seed and fertilizer also plays an important role in the concentration of fertilizer in the seed row and the risk of toxicity from seed-placed fertilizer. For example, a disc opener results in very little spreading of seed and fertilizer, compared to knife or sweep openers, increasing the contact between seed and fertilizer, resulting in greater risk of crop establishment failure (Chaudhuri 2001).

Soil texture also controls the amount of water available for seed germination, which is driven by the osmotic pressure in the soil. Coarse-textured soils are more likely to have low water content and have less capacity to dilute the fertilizer salts. Rader et al. (1943) observed that the osmotic potential changes in soil are more intense in medium to coarse-textured soils than in fine-textured soils.

The last factor affecting fertilizer toxicity is the crop’s tolerance to fertilizer`s salt. Some crops such as cereals are relatively tolerant to fertilizer placed close to the seed, which allows the application of high rates of seed-placed fertilizer. MAFRD (2007) recommends a maximum of 56 kg seed-placed P_2O_5 ha^{-1} for wheat, while the maximum for canola (*Brassica napus* L.) is 22 kg seed-placed P_2O_5 ha^{-1}, because canola is highly sensitive to fertilizer toxicity.

Research in North America on phosphorus nutrition of soybean has shown infrequent and inconsistent responses of seed yield and biomass to increased rates and placement of phosphorus fertilizer (Florence 2015; Gervais 2009; Bureau et al. 1952; Mallarino 2009; Slaton 2009; Lauzon and Miller 2008; Borges and Mallarino 2000). In most of these studies, lack of soybean response to P fertilizer was observed in neutral to high pH soils and also occurred only at very low soil P levels, levels at which other crops would respond positively to P fertilizer applications.

For some crops, “starter” fertilizer, applied in small rates with the seed is important for improving early shoot and root growth, especially in spring, when soils are cold and plant root growth is very slow. Therefore, when crops such as corn, canola and wheat are early seeded into cold soils, they often respond to seed-placed fertilizer P because of the insufficient supply of P from the seed and soil (Grant et al. 2001). Touchton and Rickerl (1986) observed soybean yield increase to 20 kg P ha^{-1} applied as a starter fertilizer regardless of the soil P background status. Conversely, Gervais (2009) conducted phosphorus fertilization trials in Manitoba and did not observe response to P, regardless of rate and placement. Soybean has large seed reserves of P, and thus is self-sufficient to supply early season P requirement (Lauzon and Miller 2008; Barber 1978). Furthermore, recommended soil temperature for seeding soybean is at least 10° C, when P diffusion and plant development are not as restricted as for other crops that are planted in colder soils.

The small amount of historic research with P fertilization of soybean in Manitoba has yielded contradictory results. Bullen et al. (1983) observed a significant seed yield increase for P fertilizer that was side-banded 2.5 cm below the seed or 2.5 cm below and 2.5 cm beside the seed when compared to seed-placed or broadcast fertilizer. However, more recent research comparing P placements did not measure any soybean yield increase from side-banded or seed-placed P fertilizer (Gervais 2009). Moreover, current soybean cultivars have greater yield potential than cultivars grown several decades ago, which creates a greater demand for P, such as reported by Kovacs and Casteel (2014), who compared yield protential and P use of past and current soybean cultivars.

Seed quality parameters such as seed size, seed oil and protein concentration may also be affected by phosphorus fertilization. However, most studies have shown inconsistent seed quality responses to P fertilizer rate and placement (Mallarino and Haq 2005; Gervais 2009; Fernandez et al. 2012).

In summary, there is a lack of information on P fertilization of modern soybean varieties in Manitoba. Therefore, the current study investigated the risk of plant stand, mid-season biomass and seed yield reduction caused by seed-placed fertilizer toxicity, and to assess the soybean biomass and seed yield response to various rates and placements of phosphorus fertilizer, as well as the effect of P fertilization on seed and biomass phosphorus concentration and uptake, seed protein and oil concentration, and seed size.

2.3. Materials and Methods

2.3.1. Experimental Sites and Treatments

During 2013, 2014 and 2015, 28 site-years of field studies were established across Manitoba in 10 different locations, including Carman, Roseisle, Portage la Prairie, Carberry, Brandon, Melita, Roblin, Arborg, Beausejour and St. Adolphe (see Appendix B for GPS coordinates). Trials at Carman and Roseisle were established in 2014 and 2015, only.

This study was established in ten different locations across Manitoba, using local equipment, which resulted in a great diversity of soil chemical and physical characteristics and seeding equipment. Soil texture ranged from sandy loam (79% sand) to heavy clay (78% clay). Soil phosphorus levels ranged from 3 to 71 mg kg^{-1} Olsen extractable P at 0-15 cm depth, with 14 site-years containing less than 10 mg kg^{-1} soil test P (Table 2.1). Soils were alkaline in general, with pH ranging from 5.3 to 8.8 at 0-15 cm depth. Seeding equipment varied with opener type, which was either knife or disc, as well as seed row spacing, which varied from 18.5 to 30.5 cm row spacing (Table 2.2). In total, nine different seeders were used during the three years of this study. Plot dimensions varied among sites; width ranged from 1.3 to 2.0 m and length from 5.0 to 9.0 m. The amount of precipitation was generally satisfactory for crop growth in 2013, 2014 and 2015 growing seasons. Precipitation deficit was observed only at Roblin in 2015, where there was only 26.2 and 19.0 mm of rainfall in May and June, respectively. Wheat was the most frequent previous crop (16 site-years) followed by canola (3 site-years) and flax (2 site-years) (Appendix B).

Table 2.1 Soil test phosphorus characterization at each site-year, in spring prior to seeding soybean.

Site	P (mg kg^{-1})[z]		
---	2013	2014	2015
Roseisle	-	4 (VL)	4 (VL)
Melita	3 (VL)[y]	5 (L)	7 (L)
Brandon	5 (L)	6 (L)	5 (L)
Carman	-	15 (H)	7 (L)
Roblin	7 (L)	22 (VH)	8 (L)
Beausejour	8 (L)	13 (M)	7 (L)
Arborg	14 (M)	22 (VH)	14 (M)
St. Adolphe	23 (VH)	25 (VH)	71 (VH)
Portage	34 (VH)	18 (H)	10 (L)
Carberry	44 (VH)	11 (M)	15 (H)

[z] Olsen extractable P determined by Agvise Laboratories (Northwood, ND. USA).

[y] Phosphorus level of sufficiency indicated by the letters VL, L, M, H and VH means very low, low, medium, high and very high, respectively (MAFRD 2007).

Table 2.2 Seeding equipment details for each of the locations.

Site	Row spacing	Opener width	SBU[z]	Seeder opener
---	----- (cm) -----		(%)	Type
Roseisle	20.3	7.6	37.4	Knife
Melita	24.1	1.9	7.9	Knife
Brandon	20.3	1.9	9.4	Knife
Carman	20.3	7.6	37.4	Knife
Roblin	22.9	2.5	10.9	Knife
Beausejour	22.9	1.3	5.7	Disc
Arborg	22.9	1.3	5.7	Disc
St. Adolphe	18.5	7.6	41.1	Knife
Portage	30.5	1.3	4.3	Disc
Carberry	30.5	1.3	4.3	Disc

[z] Seed bed utilization (SBU) values are estimated and calculated as the percent of the ratio of opener width divided by the row spacing.

Table 2.3 Soil texture classification for the sites established in 2013, 2014 and 2015.

Year	Site	Sand	Clay	Silt	Soil texture classification
		(g kg^{-1})			
2013[z]	Arborg	-	-	-	Clay
	Beausejour	-	-	-	Clay
	Brandon	-	-	-	Clay Loam
	Carberry	-	-	-	Clay Loam
	Melita	-	-	-	Loamy Sand
	Portage	-	-	-	Clay Loam
	Roblin	-	-	-	Loam
	St. Adolphe	-	-	-	Clay
2014	Arborg	85	476	439	Silty Clay
	Beausejour	217	625	158	Heavy Clay
	Brandon	308	371	321	Clay Loam
	Carberry	318	336	345	Clay Loam
	Carman	629	231	139	Sandy Clay Loam
	Melita	550	202	248	Sandy Clay Loam
	Portage	206	387	408	Clay Loam
	Roblin	407	309	284	Clay Loam
	Roseisle	738	159	103	Sandy Loam
	St. Adolphe	58	785	157	Heavy Clay
2015	Arborg	66	506	428	Silty Clay
	Beausejour	137	686	176	Heavy Clay
	Brandon	316	369	315	Clay Loam
	Carberry	351	293	357	Clay Loam
	Carman	626	225	148	Sandy Clay Loam
	Melita	506	238	256	Sandy Clay Loam
	Portage	118	423	459	Silty Clay
	Roblin	436	257	307	Loam
	Roseisle	787	108	105	Sandy Loam
	St. Adolphe[y]	-	-	-	Clay

[z] Particle size analyses were not applied to the sites established in 2013 since soil samples for the first year of study were not kept in archive. Therefore, soil texture was retrieved from the Manitoba Soil Survey (MAFRD 2016).
[y] Soil sampling at St. Adolphe was severely restricted due to a soil-borne disease quarantine. Therefore, soil texture information was retrieved from the Manitoba Soil Survey for this site in 2015.

Treatments were composed by the combination of three fertilizer placements with three fertilizer P rates, plus a control treatment, which did not receive phosphorus fertilizer. Fertilizer was applied as monoammonium phosphate (11-52-0) at rates of 22.5

kg P_2O_5 ha^{-1}, 45 kg P_2O_5 ha^{-1} and 90 kg P_2O_5 ha^{-1} in side-band, seed-placed or broadcast. For the broadcast treatments, fertilizer was spread by hand on the soil surface ahead of the seeder and incorporated into the soil only by the planting equipment. The side-band treatments were targeted to place the fertilizer five centimetres below and five centimetres beside the seeds. The seed-placed fertilizer was applied to the soil with the seeds, through the same seeder opener. There was no compensation with extra nitrogen application for the different rates of nitrogen applied at the various rates of monoammonium phosphate.

Sites located in Portage La Prairie, St. Adolphe and Roblin had fewer treatments due to the lack of equipment for side-banding the fertilizer. In 2013, these three sites had only five treatments, resulting of the combination of seed-placed and broadcast placements with 22.5 and 45 kg P_2O_5 ha^{-1} plus a control (Table 2.4). For the second and third year of study, the 90 kg P_2O_5 ha^{-1} rate of fertilizer was included as well, resulting in seven treatments at these sites, except for Roblin in 2015, where a new seeder allowed the establishment of a full sized experiment (Table 2.4).

Table 2.4 Characteristics of the reduced and full set of treatments for 2013-2015.

Treatments	Reduced set for in 2013[z]	Reduced set for 2014 and 2015[y]	Full set[x]
Control	✓	✓	✓
22.5 kg P_2O_5 ha^{-1} seed-placed	✓	✓	✓
45 kg P_2O_5 ha^{-1} seed-placed	✓	✓	✓
90 kg P_2O_5 ha^{-1} seed-placed	✗	✓	✓
22.5 kg P_2O_5 ha^{-1} side-banded	✗	✗	✓
45 kg P_2O_5 ha^{-1} side-banded	✗	✗	✓
90 kg P_2O_5 ha^{-1} side-banded	✗	✗	✓
22.5 kg P_2O_5 ha^{-1} Broadcast	✓	✓	✓
45 kg P_2O_5 ha^{-1} Broadcast	✓	✓	✓
90 kg P_2O_5 ha^{-1} Broadcast	✗	✓	✓

[z] In 2013, the sites at Portage La Prairie, St. Adolphe and Roblin had reduced set of treatments, composed of 5 treatments.
[y] In 2014, the sites at Portage La Prairie, St. Adolphe and Roblin had reduced set of treatments, composed of 7 treatments. In 2015, the sites at Portage La Prairie and St. Adolphe had reduced set of treatments, composed of 7 treatments, as well.
[x] All the other site-years had the full set of treatments, composed of 10 treatments.

The target planting window for soybean was May 15th to June 1st. Seeding depth target was 1.9 to 3.1 cm, into soil with less than 56 kg nitrate-N ha^{-1}.

2.3.2. Seed Treatment and Weed Control

The variety grown was Dekalb 24-10 RY with a plant population target of 518,700 plants per hectare. Seed was treated with fungicide, insecticide and liquid inoculant (*Bradyrhizobium japonicum*), prior to seeding. Seed treatments in 2013 and 2014 consisted of CruiserMaxx Vibrance, which contains thiamethoxam insecticide and metalaxyl, fludioxonil and sedaxane fungicides. In 2015, seed was treated with Acceleron seed treatment which contains fluxapyroxad, pyraclostrobin and metalaxyl fungicides and imidacloprid insecticide, in addition to Optimize liquid inoculant. Regardless of the seed treatment, granular inoculant (*Bradyrhizobium japonicum*) was applied to all the plots, in furrow, at the rate of 20 kg ha^{-1}.

Weeds were controlled when required with two glyphosate (540 g a.i. L^{-1}) applications at the rate of 1.6 L ha^{-1}.

2.3.3. Statistical Design

Statistical analyses for all the evaluated parameters were conducted with the Glimmix procedure of SAS 9.4 (SAS Institute, Inc. 2016). Conformity of data was analysed with the Univariate procedure using the Shapiro-Wilk test. Data analysed which did not follow a normal distribution were base 10 logarithmic transformed. Plant stand counts were analysed using the Negative Binomial distribution. Means separations between treatments were determined according to the Tukey-Kramer test with a probability level for significance of 0.05.

All trials were set up in a Randomized Complete Block experimental design as a two-way factorial (P rate x P placement) plus control. In 2013, all the sites, except for Brandon, were set up in a split-plot treatment design where rate was the main plot, randomized across each block, and placement was the subplot, plus a control treatment. In the split-plot design for 2013, block and rate were considered random effects and placement considered a fixed effect. In 2014, 2015, and Brandon in 2013, all treatments were fully randomized within each block, so block was the only random effect and the fixed effects were rate and placement. Plots were replicated four times for all site-years, except for Melita and Arborg in 2013, where plots were replicated only three times. The nine treatments originating from a combination of three rates with three placements plus one control plot were considered in the orthogonal comparisons in the statistical model.

The data from all site-years were not pooled together for a general analysis because of differences in the equipment used across the sites, the treatment designs for the first year compared to the subsequent years and the reduced number of treatments for some of the sites where side-band treatments were not possible.

2.3.4. Plant Stand Counts

Plant stand was counted at two, three and four weeks after planting at sites with the full set of treatments and only at four weeks after planting at sites with the reduced set of treatments. The number of emerged seedlings was determined in two rows, each being one metre in length at two locations per plot. Therefore, the counts were taken in a total of 4 metres of rows per plot. Research plot flags were used to indicate where plant counts were taken in order to provide consistency for counting at different dates.

2.3.5. Mid-Season Biomass

Plants were sampled at R3 growth stage (beginning pod) in order to characterize the phosphorus uptake of the plants and above ground dry matter yield. Plants were harvested in one row, on both sides of each plot. Plants were cut at ground level and shoot mass was oven dried at 60° C and weighed.

2.3.6. Seed Yield

Whole plots were harvested with the plot combine available at each research site. Samples were cleaned and the seed weight determined with a laboratory balance at actual moisture with a post harvest correction to 130 g kg^{-1} moisture. The area sampled for mid-season biomass was deducted from the plot area for the seed yield calculation. Experimental plot area varied across research sites.

2.3.7. Seed Moisture, Protein and Oil Concentration

Seed protein concentration, oil concentration, and moisture were determined with a FOSS Infract 1241 Grain Analyzer. Protein and oil concentrations were reported on a 130 g kg^{-1} moisture basis.

2.3.8. Seed and Biomass Phosphorus Concentrations

Plant biomass and grain samples were oven dried at 60° C, weighed and ground using a Thomas - Wiley Mill Grinder with a two millimetre screen. Plant tissue and grain samples were analysed for total phosphorus concentration at Agvise Laboratories (Northwood, ND. USA). Phosphorus was extracted by digestion using nitric acid and hydrogen peroxide, and concentrations were determined by inductively couple plasma emission spectrometry.

2.3.9. Soil Analysis

Routine agronomic soil chemical analyses for all experimental blocks in all site-years were done at 0 - 15 and 15 - 60 cm depth prior to the establishment of trials. Each soil sample was composed of 10 subsamples randomly collected in each block. Organic matter, phosphorus, potassium and zinc concentrations were determined at 0 - 15 cm depth. Nitrate-N, pH, salts, sulphate-S and carbonates were determined at 0 - 60 cm depth. Samples were analysed by Agvise Laboratories (Northwood, ND, USA). The complete soil analyses are presented in Appendix B. Nitrate concentration was determined by cadmium reduction, pH and salts determined by 1:1 soil:water ratio, organic matter by loss on ignition, phosphorus by sodium bicarbonate (Olsen), exchangeable potassium by ammonium acetate, sulphur (sulphate) by turbidometric method, zinc by DTPA and carbonates by pressure method.

Soil particle size analyses were determined for soil samples from 2014 and 2015 sites using the pipette method (Carter and Gregorich 2008). Soil texture was classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998). For all sites in 2013 and for St. Adolphe in 2015, soil texture was determined from soil survey information.

2.4. Results and Discussion

2.4.1. Plant Emergence

Plant stand counts were taken at four weeks after planting at all sites and also at two and three weeks at sites with a full complement of treatments. The last counting date is presented in this chapter since it defines the final plant stand at each treatment. Soybean seeding rate was calculated for a target plant population of 518,700 plants per hectare. Some site-years had overall reduced final stand caused by suboptimal soil and weather conditions during planting. A few site-years had final plant counts above the desired target, which is attributed to the small area sampled for plant counts, or by greater number of seeds released by the seeder under field conditions when compared to the calibrations conducted in the yard.

Monoammonium phosphate has a moderate salt index of 0.405 per unit of nutrient (Laboski 2008); however, when placed close to the seeds, the enhanced osmotic pressure can affect water supply to the seed for germination and seedling emergence, resulting in poor crop stand (Hoeft et al. 1975).

In the current study, there was no positive effect of fertilizer rate and placement on plant stand. Therefore, P fertilizer treatments did not increase the number of plants that emerged at any site in any year (Tables 2.5, 2.6 and 2.7). Negative effects of fertilizer rate and placement were observed at five of 28 site-years due to the significant seedling emergence reduction caused by the fertilizer placed with the seeds, when compared to the control treatment, at $P < 0.05$ level of probability. Previous research on seed-placed P fertilizer in Manitoba had contrasting results. Bullen et al. (1983) related the low soybean yield of seed-placed fertilizer to the lack of plants on those treatments. However, more recently, Gervais (2009) observed no reduction in seedling emergence when phosphate fertilizer was placed in the seedrow.

In 2013, seedling emergence was significantly reduced at Melita and Carberry, where fertilizer placed with the seed at 90 kg P_2O_5 ha^{-1} reduced plant stands by 71% and 38%, respectively, relative to the control (Table 2.5a). In Melita, the coarse-textured soil may have been the reason for the increased toxicity caused by the seed-placed fertilizer. Rader et al. (1943) observed that the increase in soil solution osmotic pressure was more intensified in medium to coarse-textured soils when increased fertilizer rates were applied, in comparison to clay soils. At Carberry, fertilizer toxicity was promoted by the medium to coarse-textured soils in combination with the low seed bed utilization (4.3%), resulting from the wide row spacing (30.5 cm) and narrow disc opener spreading width (1.3 cm). At Beausejour, the plant stand for P broadcast at 45 kg P_2O_5

ha^{-1} was lower than at 90 kg P_2O_5 ha^{-1}, so that difference was likely a random event. The significant ANOVA values observed for Portage and St. Adolphe in 2013 were not reflected in the Tukey-Kramer test and therefore, the means separation groups did not indicate the significant effects reported by those ANOVA *P* values (Table 2.5b). No other reductions in plant stand were observed in 2013 (Tables 2.5a and 2.5b).

Table 2.5a Plant stand means at four weeks after planting by site in 2013 as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013				
		Thousand plants ha^{-1}				
-	0	441	459	407*ab*	239*a*	613*a*
Seed-Placed	22.5	423	430	421*ab*	272*a*	397*a*
	45	461	422	445*ab*	220*a*	405*a*
	90	462	349	440*ab*	147*b*	180*b*
Side-Band	22.5	490	445	459*ab*	269*a*	424*a*
	45	413	410	415*ab*	230*a*	382*a*
	90	470	495	413*ab*	237*a*	439*a*
Broadcast	22.5	417	494	469*ab*	278*a*	522*a*
	45	467	401	346*b*	244*a*	448*a*
	90	438	475	486*a*	234*a*	597*a*
Mean		448	438	430	237	441
ANOVA		$P > F$				
Rate		0.8352	0.5503	0.1464	0.0168	0.0891
Placement		0.8467	0.2596	0.9432	0.0011	<.0001
Rate*Placement		0.3607	0.3415	0.0315	0.0027	0.0005
CV (%)		16.53	18.41	14.69	19.78	34.00

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.5b Plant stand means at four weeks after planting by site in 2013 as affected by P fertilizer rate and placement.

Treatment		Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2013		
		Thousand plants ha^{-1}		
-	0	650	275*a*	207
Seed-Placed	-	558	238*a*	194
Broadcast	-	600	302*a*	190
-	0	650	275	207*a*
Seed-Placed	22.5	628	264	181*a*
	45	497	215	200*a*
Broadcast	22.5	562	303	164*a*
	45	640	301	216*a*
Mean		595	272	194
ANOVA		$P > F$		
Rate		0.5775	0.2784	0.3045
Placement		0.4513	0.0231	0.7894
Rate*Placement		0.0710	0.2754	0.0285
CV (%)		22.94	19.14	29.70

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Only two site-years had diminished plant stands relative to the control in 2014 (Tables 2.6a and 2.6b). Seedling emergence was reduced at all rates of phosphorus fertilizer placed with the seed at Portage. This significant effect of placement reduced plant stand by 37, 38 and 50% when the fertilizer was applied with the seed at 22.5, 45 and 90 kg P_2O_5 ha^{-1}, respectively. At Carberry, plant stand was reduced by 36 and 39% at 45 and 90 kg P_2O_5 ha^{-1} placed with the seed, respectively (Tables 2.6a and 2.6b).

The fertilizer toxicity observed at Portage la Prairie and Carberry appears to be induced by the clay loam soil texture and high concentration of fertilizer close to the seeds, caused by the 30.5 cm row spacing and the disc opener type, what has very low seed bed utilization (4.3%). As observed by Chaudhuri (2001), knife openers cause greater soil disturbance than a disc opener, widening the spread of seeds and may also mix moist soil from deeper layers with seeds and fertilizer. These factors may explain why less fertilizer toxicity observed in sites where the knife opener type was used, than where disc openers were used.

The significant interaction of rate and placement reported in the ANOVA table for Carman in 2014 was not reflected in the Tukey-Kramer test. As a result, means separation groups did not indicate differences among treatments (Table 2.6b).

At Brandon in 2014, the rate of 90 kg P_2O_5 ha^{-1} had reduced plant stand compared to the rate of 22.5 kg P_2O_5 ha^{-1}, but was not different from the control (Table 2.6a). At Roseisle in 2014, the seed-placed and broadcast treatments had greater plant stand than the side-band treatment, but none of them was different from the control (Table 2.6b). Therefore, the effects observed at these two site-years cannot be attributed to fertilizer toxicity.

Table 2.6a Plant stand means at four weeks after planting by site in 2014 as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014				
		Thousand plants ha^{-1}				
-	0	594*ab*	478	421	402	288
-	22.5	611*a*	491	436	379	377
-	45	585*ab*	470	428	340	331
-	90	528*b*	520	416	334	344
-	0	595	478	421	402*ab*	288
Seed-Placed	22.5	643	489	405	303*bc*	337
	45	573	478	443	258*c*	331
	90	458	481	396	246*c*	334
Side-Band	22.5	580	446	465	496*a*	438
	45	606	421	427	349*abc*	336
	90	578	563	396	394*ab*	395
Broadcast	22.5	612	541	440	361*abc*	364
	45	574	514	416	435*ab*	327
	90	554	519	457	386*ab*	309
Mean		577	493	427	363	344
ANOVA		$P > F$				
Rate		0.0158	0.3115	0.8838	0.1265	0.3677
Placement		0.4258	0.2624	0.8541	<.0001	0.1927
Rate*Placement		0.0911	0.2980	0.8291	0.0284	0.7784
CV (%)		14.50	16.59	21.70	24.50	24.36

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.6b Plant stand means at four weeks after planting by site in 2014 as affected by P fertilizer rate and placement.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		Thousand plants ha^{-1}				
-	0	643	520*ab*	530	619*a*	356
Seed-Placed	-	606	617*a*	496	359*b*	319
Side-Band	-	572	475*b*	-	-	-
Broadcast	-	601	617*a*	460	577*a*	356
-	0	643*a*	520	530	619	356
Seed-Placed	22.5	673*a*	589	478	392	370
	45	661*a*	600	533	383	302
	90	501*a*	664	478	308	290
Side-Band	22.5	590*a*	488	-	-	-
	45	501*a*	474	-	-	-
	90	633*a*	460	-	-	-
Broadcast	22.5	634*a*	580	476	584	408
	45	606*a*	586	418	539	297
	90	566*a*	691	489	609	357
Mean		601	565	486	491	340
ANOVA		$P > F$				
Rate		0.2226	0.2402	0.9608	0.6047	0.1956
Placement		0.6308	<.0001	0.2986	<.0001	0.4195
Rate*Placement		0.0461	0.4243	0.2646	0.2051	0.7500
CV (%)		17.36	17.84	17.00	28.63	29.72

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Fertilizer toxicity was intensified at Roblin in 2015 by the dry conditions of the clay loam soil, as consequence of the low precipitation during the spring. Plant stand at this site was reduced by 40% when 90 kg P_2O_5 ha^{-1} was applied in the seedrow (Table 2.7b). Similar results were obtained by Dubetz et al. (1959) when reduced soil moisture increased fertilizer toxicity and reduced germination of field beans (*Phaseolus vulgaris*).

At Melita in 2015, the rate of 90 kg P_2O_5 ha^{-1} reduced plant stand when compared to the 45 kg P_2O_5 ha^{-1}, but was unaffected by placement (Table 2.7a). At this same year in St. Adolphe, the rate of 90 kg P_2O_5 ha^{-1} had greater seedling emergence than the 22.5 and 45 kg P_2O_5 ha^{-1} treatments (Table 2.7b). These effects cannot be attributed to the seed-placed fertilizer toxicity and are likely random events. The significant ANOVA *P* values observed for Carman 2015 were not reflected by the Tukey-Kramer test. Therefore, the means separation groups did not indicate significant differences among placement methods (Table 2.7b).

Besides reducing final plant stands, fertilizer toxicity from seed placed fertilizer can also delay seedling emergence. Therefore, at sites where plant emergence was counted weekly, the data was tested for an interaction between fertilizer treatment and time. There was a significant effect of time since plant stand counts at four weeks after planting were greater than at two and three weeks after planting for some sites (Appendix C). However, there was no interaction between rate, placement and time, indicating that the rate of emergence was not affected by P fertilizer rate or placement.

Table 2.7a Plant stand means at four weeks after planting by site in 2015 as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Thousand plants ha^{-1}				
-	0	431	466	519	174	324*ab*
-	22.5	430	470	-	266	351*ab*
-	45	497	493	525	243	395a
-	90	408	433	526	199	320*b*
-	0	431	466	519	174	324
Seed-Placed	22.5	474	453	-	244	378
	45	498	476	547	291	409
	90	403	405	588	141	324
Side-Band	22.5	434	523	578	236	350
	45	547	482	513	195	389
	90	409	482	447	295	319
Broadcast	22.5	388	438	487	328	326
	45	449	521	515	252	389
	90	412	414	554	189	319
Mean		445	466	528	235	353
ANOVA		*P > F*				
Rate		0.1627	0.1213	0.7499	0.2201	0.0152
Placement		0.5592	0.1882	0.3007	0.6709	0.5640
Rate*Placement		0.8575	0.4690	0.0777	0.0776	0.9511
CV (%)		26.32	17.01	15.08	38.77	17.34

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.7b Plant stand means at four weeks after planting by site in 2015 as affected by P fertilizer rate and placement.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Thousand plants ha^{-1}				
-	0	526	745	464	446	440*ab*
-	22.5	513	673	452	480	425*b*
-	45	525	622	391	469	424*b*
-	90	547	662	404	423	528*a*
-	0	526*a*	745	464	446	440
Seed-Placed	-	496*a*	659	348	481	438
Side-Band	-	556*a*	620	451	-	-
Broadcast	-	534*a*	679	455	434	476
-	0	526	745	464*a*	446	440
Seed-Placed	22.5	518	726	414*a*	504	402
	45	510	569	368*ab*	500	409
	90	462	694	277*b*	442	510
Side-Band	22.5	517	600	466*a*	-	-
	45	532	634	435*a*	-	-
	90	625	626	453*a*	-	-
Broadcast	22.5	503	700	479*a*	457	449
	45	534	669	373*ab*	440	440
	90	567	670	526*a*	406	546
Mean		529	663	423	455	446
ANOVA		$P > F$				
Rate		0.3487	0.1399	0.0632	0.1932	0.0085
Placement		0.0488	0.0823	0.0002	0.0863	0.1684
Rate*Placement		0.0652	0.0519	0.0037	0.9513	0.9503
CV (%)		13.52	12.19	20.51	14.09	16.75

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

The results of this study indicates that the tolerance of soybean for seed-placed fertilizer seems to be underestimated in the provincial guidelines, which recommend a maximum of 11.2 kg P_2O_5 ha^{-1} to be applied within the seedrow if row spacings are 38 cm or less. Fertilizer seed-placed at 22.5 kg P_2O_5 ha^{-1} reduced plant emergence at only one site-year, 45 kg P_2O_5 ha^{-1} seed-placed at only two site-years and 90 kg P_2O_5 ha^{-1} seed-placed at five site-years, compared to the control. Therefore, placing phosphorus fertilizer close to the seeds appears to be safer than previously thought. However, fertilizer toxicity can be aggravated by many factors such as low soil moisture, coarse soil texture, wide row spacing and low disturbance seeder openers, which vary the maximum safe rate of seed placed P from field to field and year to year. Furthermore, during the three years of this study, low soil moisture was generally not a limiting factor, which could otherwise have increased fertilizer toxicity.

2.4.2. Mid-season Biomass Yield

Similar to other studies (Gervais 2009; Borges and Mallarino 2000; Mallarino 2009) mid-season biomass was rarely affected by phosphorus fertilizer rate and placement (Tables 2.8, 2.9 and 2.10). Mid-season biomass dry matter was significantly reduced by P fertilization when compared to the control at only two locations.

Reasonable amounts of biomass were accumulated by R3 growth stage; however, statistical differences between treatment means of biomass yield were difficult to detect because of the large variation resulting from sampling only two metres of plant rows in each plot. Mid-season biomass yield was not increased by P fertilization at any site-year but was reduced at two site-years. Seedrow P was not responsible for the reduction in biomass yield at either of these site-years.

Despite the biomass reduction of 59% for the 90 kg P_2O_5 ha^{-1} seed-placed fertilizer relative to the control at Melita in 2013, *P* values indicate no significant statistical difference, possibly due to the high coefficient of variation of 34% (Table 2.8b). The significant effect of placement at this site indicates that side-banded treatments had reduced biomass yield relative to the broadcast and control treatments, which was probably a random error effect for not being logically explained by the placement effect.

Biomass yield for the treatment of 45 kg P_2O_5 ha^{-1} broadcast was significantly reduced relative to the control at Beausejour in 2013; however, this reduction in biomass cannot be attributed to the effect of fertilizer in this treatment, either, given that the biomass yields for broadcast rates, that were higher or lower than 45 kg P_2O_5 ha^{-1}, were not different from the control (Table 2.8a).

The ANOVA for Carberry in 2013 and Brandon in 2014 indicated significant *P* values but the treatment effects were not strong enough to be detected by the Tukey-Kramer test (Tables 2.8b and 2.9a). The side-band treatments increased biomass yield in Carberry in 2014, compared to the seed-placed treatments but were not different from the control (Table 2.9a). In 2015, Brandon had greater biomass yield for the 45 kg P_2O_5 ha^{-1} treatments compared to the 90 kg P_2O_5 ha^{-1} treatments, and in Roblin, biomass for the 90 P_2O_5 ha^{-1} side-banded treatment was greater than the 90 P_2O_5 ha^{-1} seed-placed treatment. In both site-years, none of these treatments resulted in biomass yields that were different from the control (Tables 2.10a and 2.10b).

In addition to the large coefficient of variation for the means of these data, another reason for the infrequent differences in biomass between treatments is that soybean plants have great compensatory growth ability which is responsible for extra branch growth when plant stand is reduced, increasing total dry matter and number of branch per plant (Carpenter and Board 1997). Therefore, treatments where the plant stand was reduced by seedling toxicity were probably able to compensate with increased vegetative growth per plant. Sampling plants in a certain length of the plot was useful to check for the relation of plant stand with biomass growth and P uptake, which could be influenced by the compensatory growth of the plants. If we had sampled an exact number of plants per plot, similar to that reported by Mallarino et al. (2009), the effect of fertilizer rate on each plant would be more easily measured; however, the overall effect of seed-placed fertilizer, would not.

Table 2.8a Mid-season (R3) biomass yield means by site in 2013, as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour
Placement	Rate (kg P_2O_5 ha^{-1})	2013		
		Biomass (kg ha^{-1})		
-	0	5563	4953	5616*a*
Seed-Placed	22.5	6423	5594	4837*ab*
	45	5370	5336	5476*a*
	90	5548	4028	4557*ab*
Side-Band	22.5	5335	4805	4738*ab*
	45	4811	5321	5092*a*
	90	5660	5232	4963*ab*
Broadcast	22.5	4560	5399	4697*ab*
	45	5340	4520	3423*b*
	90	6212	4292	5374*a*
Mean		5482	4948	4877
ANOVA		$P > F$		
Rate		0.2715	0.4425	0.7417
Placement		0.3833	0.6116	0.1123
Rate*Placement		0.1247	0.2512	0.0010
CV (%)		18.35	19.29	17.96

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.8b Mid-season (R3) biomass yield means by site in 2013, as affected by P fertilizer rate and placement.

Treatment		Carberry	Melita	Roblin
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2013		
		Biomass ($kg\ ha^{-1}$)		
-	0	6245*a*	7056*a*	7152
Seed-Placed	-	5687*a*	4753*a*	6636
Side-Band	-	6961*a*	4361*a*	-
Broadcast	-	6871*a*	6258*a*	7281
-	0	6245	7056	7152
Seed-Placed	22.5	5926	5731	6142
	45	5087	5667	7130
	90	6048	2861	-
Side-Band	22.5	6949	5160	-
	45	6526	3332	-
	90	7408	4593	-
Broadcast	22.5	7001	6247	7824
	45	6725	5608	6738
	90	6887	6921	-
Mean		6480	5317	6997
ANOVA		$P > F$		
Rate		0.4312	0.3196	0.9419
Placement		0.0415	0.0231	0.3467
Rate*Placement		0.9646	0.0796	0.1414
CV (%)		20.46	33.78	18.69

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.9a Mid-season (R3) biomass yield means by site in 2014, as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry
Placement	Rate (kg P_2O_5 ha^{-1})	2014			
		Biomass (kg ha^{-1})			
-	0	2313	3563	3122	4235*ab*
Seed-Placed	-	2451	4046	2974	3339*b*
Side-Band	-	2603	3906	3594	4642*a*
Broadcast	-	2385	4073	3415	4091*ab*
-	0	2313*a*	3563	3122	4235
Seed-Placed	22.5	2398*a*	3455	2917	3060
	45	2871*a*	4391	3546	3291
	90	2085*a*	4291	2459	3667
Side-Band	22.5	2450*a*	3571	3518	5015
	45	2437*a*	3801	3731	4463
	90	2920*a*	4346	3532	4449
Broadcast	22.5	2574*a*	4388	3321	4135
	45	2323*a*	3945	2994	4069
	90	2257*a*	3885	3930	4068
Mean		2463	3964	3307	4045
ANOVA		$P > F$			
Rate		0.6900	0.4198	0.8155	0.9375
Placement		0.3059	0.8159	0.0838	0.0113
Rate*Placement		0.0092	0.1856	0.0853	0.8201
CV (%)		16.10	18.91	22.02	26.09

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.9b Mid-season (R3) biomass yield means by site in 2014, as affected by P fertilizer rate and placement.

Treatment		Melita	Carman	Roseisle
Placement	Rate (kg P_2O_5 ha^{-1})	2014		
		Biomass (kg ha^{-1})		
-	0	3020	4216	2373
Seed-Placed	22.5	3626	3418	2949
	45	3683	3925	2331
	90	2821	3476	2644
Side-Band	22.5	3962	3933	2393
	45	3653	4523	2634
	90	3636	4373	3023
Broadcast	22.5	3809	4057	2628
	45	2868	3758	2438
	90	3249	5225	2819
Mean		3433	4090	2623
ANOVA		$P > F$		
Rate		0.1555	0.3840	0.4078
Placement		0.2773	0.1367	0.9766
Rate*Placement		0.4534	0.3517	0.6381
CV (%)		23.07	26.61	23.53

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.10a Mid-season (R3) biomass yield means by site in 2015, as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry
Placement	Rate (kg P_2O_5 ha^{-1})	2015			
		Biomass (kg ha^{-1})			
-	0	3345*ab*	2360	4858	3263
-	22.5	3340*ab*	2503	-	3167
-	45	3777*a*	2805	5146	3774
-	90	2571*b*	2951	4794	3201
-	0	3345	2360	4858	3263
Seed-Placed	22.5	3839	2133	-	2992
	45	3628	2530	4713	4158
	90	2215	2733	4304	2690
Side-Band	22.5	3676	2693	5057	2898
	45	4113	2692	5287	3588
	90	3018	2837	4333	3668
Broadcast	22.5	2505	2681	5474	3612
	45	3591	3193	5438	3577
	90	2480	3284	5744	3244
Mean		3241	2714	5023	3369
ANOVA		*P > F*			
Rate		0.0193	0.3503	0.8046	0.4580
Placement		0.2049	0.1852	0.2429	0.9347
Rate*Placement		0.5721	0.9527	0.7546	0.7064
CV (%)		33.15	27.97	24.56	36.54

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.10b Mid-season (R3) biomass yield means by site in 2015, as affected by P fertilizer rate and placement.

Treatment		Melita	Carman	Roseisle	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2015			
		Biomass (kg ha^{-1})			
-	0	3819	3011	4526	3262*ab*
Seed-Placed	22.5	4398	4217	3318	3300*ab*
	45	3653	4067	3303	2864*ab*
	90	4057	4156	4065	2494*b*
Side-Band	22.5	4192	4186	3614	3111*ab*
	45	3529	4859	3509	3233*ab*
	90	3391	4497	3686	3686*a*
Broadcast	22.5	4758	4056	3654	3025*ab*
	45	4669	3910	4109	2926*ab*
	90	3638	4209	3658	2783*ab*
Mean		4010	4117	3744	3069
ANOVA		$P > F$			
Rate		0.0827	0.9103	0.7256	0.5898
Placement		0.1591	0.3916	0.7491	0.0160
Rate*Placement		0.5191	0.8450	0.6713	0.0354
CV (%)		21.08	24.83	23.96	16.52

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

2.4.3. Mid-season Biomass Phosphorus Concentration

Biomass P concentration was affected by P fertilizer rate and placement at 8 of 28 site-years (Tables 2.11a and 2.11b). In 6 of those 8 responsive site-years, the concentration of P in the biomass increased with increases in the rate of fertilizer P, as would be expected.

In 2013, broadcast placement had greater P concentration relative to the control at Melita but seed-placed did not (Table 2.11a). At this location, plant stand was reduced substantially at 90 kg P_2O_5 ha^{-1} seed-placed. Thus, P concentration would be expected to be higher for the seed-row placed P treatment since there was more P accessible per plant, unlike in the broadcast treatments, where there was no reduction in plant stand. Regardless of P rate or placement, P fertilization increased biomass P concentration at Brandon in 2013 (Table 2.11a).

In 2014, side banded and seed-placed fertilizer increased plant tissue P concentration at Roseisle (Table 2.11a). This site-year also had a significant effect of placement on seedling emergence, which was reduced in the side-banded treatments. Although the lack of plants might not be attributed to the side-band treatments, the lower population of plants in this treatment had a larger supply of P per plant, increasing mid-season biomass P concentration. At Melita in 2014, the rate of 90 kg P_2O_5 ha^{-1} increased plant tissue P concentration compared to the other treatments, including the control (Table 2.11a).

At Carman in 2015, treatments that received broadcast P had greater biomass P concentrations than in the control or side-band P treatments (Table 2.11b). Conversely, at Melita in this same year, seed-placed P produced greater biomass P concentration than for broadcast or control treatments. Also in 2015, the sites at Brandon, Melita and Roseisle had increases in plant tissue P concentration relative to the control for P fertilizer added at 90 kg P_2O_5 ha^{-1}, 90 and 45 kg P_2O_5 ha^{-1}, and all rates of P, respectively (Table 2.11b).

Increased P concentration in plant tissue as a response to P fertilization may not always occur or it is inconsistent, as observed in other studies (Slaton et al. 2010; Lauzon and Miller 2008; Mallarino et al. 2009). The responses to increased rate of P fertilizer observed in 6 of 28 site-years indicate that in some cases plants will capitalize on the extra phosphorus that is available and will absorb it. Furthermore, all the eight sites where biomass P concentration increased in response to P rate or placement had low soil P test (< 10 mg kg^{-1} Olsen extractable P).

As mentioned previously, we had expected that high rates of seed-placed fertilizer would reduce plant stand and therefore, increase the content of P accessible per plant, or increased rates of P fertilizer would enhance P availability, as well. However, there was no significant interaction of fertilizer rate and placement at any site for mid-season dry matter phosphorus concentration.

Table 2.11a Sites with significant effects of P fertilization on plant tissue P concentration in 2013 and 2014.

Treatment		Melita	Brandon	Roseisle	Melita
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2013	2013	2014	2014
		Plant tissue P concentration ($g\ kg^{-1}$)			
-	0	2.6	2.1*c*	2.0*b*	2.8*b*
-	22.5	2.9	2.4*b*	2.3*ab*	3.1*b*
-	45	2.9	2.5*ab*	2.2*ab*	3.1*b*
-	90	3.4	2.6*a*	2.4*a*	3.5*a*
-	0	2.6*b*	2.1*c*	2.0*c*	2.8
Seed-Placed	-	3.1*ab*	2.5*ab*	2.3*ab*	3.3
Side-Band	-	2.9*ab*	2.6*a*	2.4*a*	3.3
Broadcast	-	3.2*a*	2.4*b*	2.2*bc*	3.2
-	0	2.6	2.1	2.0	2.8
Seed-Placed	22.5	2.9	2.3	2.2	3.2
	45	2.8	2.5	2.4	3.2
	90	3.7	2.6	2.5	3.5
Side-Band	22.5	2.9	2.4	2.5	3.2
	45	2.7	2.7	2.2	3.1
	90	3.1	2.8	2.6	3.5
Broadcast	22.5	2.9	2.4	2.1	3.0
	45	3.2	2.2	2.2	3.1
	90	3.4	2.5	2.2	3.6
Mean		3.0	2.4	2.3	3.2
ANOVA		$P > F$			
Rate		0.07	0.0033	0.0166	0.0073
Placement		0.0332	0.0129	0.0024	0.8459
Rate*Placement		0.0671	0.1808	0.0755	0.889
CV (%)		13.32	11.13	10.87	11.74

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.11b Sites with significant effects of P fertilization on plant tissue P concentration in 2015.

Treatment		Melita	Brandon	Carman	Roseisle
Placement	Rate (kg P_2O_5 ha^{-1})	2015	2015	2015	2015
		Plant tissue P concentration (g kg^{-1})			
-	0	2.2*c*	2.4*b*	2.1	1.8*d*
-	22.5	2.4*c*	2.5*b*	2.3	2.0*c*
-	45	2.5*b*	2.7*ab*	2.3	2.2*b*
-	90	2.7*a*	2.9*a*	2.4	2.4*a*
-	0	2.2*c*	2.4	2.1*b*	1.8
Seed-Placed	-	2.6*a*	2.7	2.3*ab*	2.2
Side-Band	-	2.5*ab*	2.7	2.2*b*	2.1
Broadcast	-	2.4*b*	2.7	2.5*a*	2.2
-	0	2.2	2.4	2.1	1.8
Seed-Placed	22.5	2.4	2.4	2.3	2.1
	45	2.6	2.8	2.2	2.2
	90	2.9	2.9	2.4	2.4
Side-Band	22.5	2.4	2.6	2.3	1.8
	45	2.5	2.6	2.3	2.2
	90	2.7	3.0	2.2	2.4
Broadcast	22.5	2.2	2.4	2.4	2.1
	45	2.4	2.8	2.4	2.1
	90	2.6	2.9	2.7	2.4
Mean		3.2	2.7	2.3	2.1
ANOVA		*P > F*			
Rate		<.0001	0.0004	0.1019	0.0001
Placement		0.0011	0.9384	0.0033	0.1240
Rate*Placement		0.6199	0.2774	0.3159	0.0827
CV (%)		9.54	18.31	9.36	11.34

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

2.4.4. Mid-season Biomass Phosphorus Uptake

Phosphorus uptake was determined by the combination of biomass yield with the biomass P concentration. Therefore, greater P uptake was obtained as a consequence of high biomass yield and/or high tissue P concentration. Only two site-years had P fertilization treatments where P uptake was significantly greater than the control:

Brandon in 2013 for the rate of 90 kg P_2O_5 ha^{-1} and Brandon in 2014, where greater P uptake was obtained with 90 kg P_2O_5 ha^{-1} side-banded (Table 2.12).

At Melita in 2013, broadcast treatments had greater P uptake than seed-placed and side-banded treatments, which corresponded with the biomass yield reduction observed for the side-band treatments relative to the control, with the greater plant tissue P concentration for the broadcast treatments at this site-year and with the plant stand reduction for the 90 kg P_2O_5 ha^{-1} seed-placed (Table 2.12). At Beausejour in 2013, biomass P uptake was reduced at 45 kg P_2O_5 ha^{-1} broadcast compared to 90 kg P_2O_5 ha^{-1} broadcast and 45 kg P_2O_5 ha^{-1} seed-placed. This site also had decreased plant stand at 45 kg P_2O_5 ha^{-1} broadcast relative to 90 kg P_2O_5 ha^{-1} broadcast (Table 2.8a). Therefore, the shortage of plant biomass in this treatment reduced plant P uptake.

Carberry 2014 and Roblin 2015 had greater P uptake for the side-band treatments relative to the seed-placed treatments (Table 2.12), which could be attributed to the similar treatment effects on biomass (Tables 2.9a and 2.10b). Even though neither of these placements was significantly different from the control, their numerical differences are more prominent when compared to each other, resulting in a statistically significant difference. Furthermore, both site-years had significant plant stand decreases caused by seed-placed fertilizer, which can reduce P uptake if plant tissue P concentration was not enhanced at those treatments or if the compensatory growth did not overcome the lack of plants.

Table 2.12 Sites with significant effects of P fertilization on plant tissue P uptake.

Treatment		Brandon	Melita	Beausejour	Carberry	Brandon	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2013	2013	2013	2014	2014	2015
		Plant tissue P uptake (kg ha^{-1})					
-	0	11.4*b*	18.1	10.8	9.1	5.6	9.2
-	22.5	12.7*b*	16.5	9.6	9.2	6.3	9.0
-	45	12.7*b*	14.2	9.9	8.5	6.8	8.6
-	90	15.3*a*	16.2	11.0	9.3	6.9	8.8
-	0	11.4	18.1*ab*	10.8	9.1*ab*	5.6	9.2*ab*
Seed-Placed	-	14.2	14.2*b*	10.5	7.4*b*	6.5	8.1*b*
Side-Band	-	13.7	12.7*b*	10.1	10.5*a*	6.9	9.7*a*
Broadcast	-	12.8	20.0*a*	9.9	9.1*ab*	6.6	8.6*ab*
-	0	11.4	18.1	10.8*ab*	9.1	5.6*b*	9.2
Seed-Placed	22.5	14.7	16.3	9.6*ab*	6.5	6.3*ab*	9.0
	45	13.5	15.7	11.5*a*	6.9	7.4*ab*	7.8
	90	14.4	10.4	10.4*ab*	8.6	6.0*b*	7.6
Side-Band	22.5	12.6	14.1	10.1*ab*	11.6	5.8*b*	9.3
	45	12.7	9.0	10.7*ab*	9.7	6.5*ab*	9.4
	90	15.8	15.0	9.5*ab*	10.3	8.4*a*	10.3
Broadcast	22.5	10.8	18.2	9.7*ab*	9.4	6.8*ab*	8.9
	45	11.9	17.8	7.5*b*	8.8	6.7*ab*	8.6
	90	15.6	23.9	12.6*a*	9.0	6.2*ab*	8.4
Mean		13.3	15.9	10.2	9.0	6.6	8.8
ANOVA		$P > F$					
Rate		0.0104	0.4849	0.4090	0.6269	0.2818	0.6628
Placement		0.2893	0.0054	0.6273	0.0063	0.5859	0.0151
Rate*Placement		0.2741	0.1070	0.0043	0.6176	0.0046	0.4076
CV(%)		20.77	34.9	21.89	31.7	17.49	20.25

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

2.4.5. Seed Yield

Soybean seed yield ranged from 951 to 4887 kg ha $^{-1}$ with average yields of 3102, 2792 and 3480 kg ha^{-1} in 2013, 2014 and 2015, respectively. In general, average yields in our research plots were greater than the 2013, 2014 and 2015 provincial averages of 2587, 2243 and 2580 kg ha^{-1}, respectively (Manitoba Agricultural Services Corporation 2016). Seed yield was increased by P fertilization at one of the 28 site-years and was decreased at two site-years, as consequence of the drastic plant stand reduction caused by seed-placed P fertilizer, which reduced plant stand to less than 247.000 plants.ha^{-1}.

At Roseisle in 2015, there was approximately 15% more seed yield for the rates of 90 and 45 kg P_2O_5 ha^{-1}, compared to the control (Table 2.15b). This low frequency of response to P is similar to other research conducted on phosphorus fertilization for soybean in North America (Borges and Mallarino 2000; Slaton et al. 2010; Lauzon and Miller 2008; Mallarino and Haq 2005; Gervais 2009; Florence 2015).

A large number of site-years in this study (50%) are characterized by very low and low levels of soil test P (below 10 mg kg^{-1}) in which most of the field crops grown in Western Canada would respond positively to P fertilization. For example, Karamanos et al. (2010) observed that hard red spring wheat responded to P fertilizer in 100% of sites where soil test P was lower than 5 mg kg^{-1} Olsen P, in a study conducted over 47 site-years. In our study, the control plots yielded as much as the fertilized plots in five of six sites with Olsen soil test P values of 5 mg kg^{-1} or less, such as the site at Melita in 2013, where the fertilized treatments did not increase yield when compared to the control, which had a mean seed yield of 3971 kg ha^{-1}. Soybean seems to have great ability for exploring soil P pools that are less explored by other crops, and are not extracted by the standard soil P analysis. This use of soil P reservoirs may be due to the rhizosphere acidification promoted by legumes (Li et al. 2011; Raven et al. 1990), dissolving phosphates such as calcium phosphates (Gahoonia and Nielsen 1992), which are the main form of P minerals in Manitoba soils.

Seed yield was reduced by P fertilization in two site-years. In 2013, seed yield relative to the control was reduced by 29 and 36% at Carberry and Melita, respectively, for 90 kg seed-placed P_2O_5 ha^{-1} (Table 2.13a). At both sites, fertilizer toxicity caused by this treatment drastically reduced plant stand below 247,000 plants per hectare, which is considered the threshold plant population for replanting soybean (Lee et al. 2008; Conley and Gaspar 2015; Mohr et al. 2014). Plant stand reductions for seed row P were observed at five site-years, but the severity of the plant stand reduction resulted in seed yield decreases at only two site-years. This absence of reductions on seed yield could be explained by the compensatory growth ability of the soybean plants, which produce more branches and pods when plant stand is suboptimal (Carpenter and Board 1997). Even though the low plant population reduced seed yield at two site-years, there was no effect on biomass accumulation that could be detected, probably due to the high coefficient of variation resulting of the small area sampled for mid-season biomass.

At Brandon in 2014 and Roblin in 2015, the side-band treatments had greater seed yield than the seed-placed treatments; however, none of the fertilized treatments was different from the control (Tables 2.14a and 2.15b). At Roblin, there was an increase in biomass yield and P uptake for the side-band treatment relative to the seed-placed, which could be the reason for this effect on seed yield. However, the effect observed at Brandon was likely a random event because it was not related to effects on plant stand and biomass yield, and biomass P concentration and P uptake. Significant ANOVA *P* values were observed for the sites at Brandon, Arborg and St. Adolphe in 2013, Carberry and Portage in 2014, and Carman in 2015, but were not reflected in the

Tukey-Kramer analyses and therefore, the means separation groups did not indicate differences between treatments.

Table 2.13a Means of soybean seed yield in 2013 sites as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013				
		kg ha^{-1}				
-	0	2341*a*	2372*a*	3812	3536	3971
Seed-Placed	-	2065*a*	2542*a*	4177	3105	3335
Side-Band	-	2329*a*	2504*a*	3919	3301	3472
Broadcast	-	2084*a*	2773*a*	4087	3304	3729
-	0	2341	2372	3812	3536*a*	3971*a*
Seed-Placed	22.5	2160	2691	4063	3651*a*	3760*a*
	45	2254	2524	4182	3162*a*	3700*a*
	90	1837	2412	4285	2504*b*	2546*b*
Side-Band	22.5	2224	2423	3782	3417*a*	3246*ab*
	45	2126	2443	3970	3296*a*	3438*ab*
	90	1845	2646	4005	3189*a*	3733*a*
Broadcast	22.5	2341	2723	4031	3184*a*	3592*ab*
	45	2267	2605	4144	3539*a*	3785*a*
	90	2381	2992	4085	3188*a*	3808*a*
Mean		2178	2583	4036	3267	3558
ANOVA		$P > F$				
Rate		0.0611	0.6536	0.3054	0.0164	0.4525
Placement		0.0186	0.0106	0.0930	0.0593	0.0780
Rate*Placement		0.1926	0.0661	0.9610	0.0005	0.0046
CV (%)		13.81	13.11	7.05	12.19	16.74

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.13b Means of soybean seed yield in 2013 sites as affected by P fertilizer rate and placement.

Treatment		Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})		2013	
			kg ha^{-1}	
-	0	1540	3168	4432*a*
Seed-Placed	-	1598	3080	4736*a*
Broadcast	-	1650	2948	4402*a*
-	0	1540	3168	4432
Seed-Placed	22.5	1672	2875	4639
	45	1524	3022	4833
Broadcast	22.5	1656	3160	4264
	45	1645	3001	4540
Mean		1607	3045	4542
ANOVA			$P > F$	
Rate		0.4606	0.9690	0.0929
Placement		0.4953	0.3954	0.0232
Rate*Placement		0.3722	0.3259	0.7570
CV (%)		12.18	9.49	9.15

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.14a Means of soybean seed yield in 2014 sites as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})			2014		
				kg ha^{-1}		
-	0	1177*ab*	3513	2441	2905*a*	3483
Seed-Placed	-	1149*b*	3618	2362	3004*a*	3344
Side-Band	-	1359*a*	3715	2414	3346*a*	3544
Broadcast	-	1267*ab*	3499	2396	3231*a*	3400
-	0	1177	3513	2441	2905	3483
Seed-Placed	22.5	1270	3591	2500	3176	3454
	45	1226	3637	2303	3003	3398
	90	951	3625	2283	2831	3181
Side-Band	22.5	1351	3573	2293	3380	3775
	45	1343	3731	2521	3402	3646
	90	1384	3840	2428	3256	3212
Broadcast	22.5	1193	3721	2380	3311	3337
	45	1278	3318	2327	3092	3280
	90	1330	3458	2482	3290	3585
Mean		1250	3600	2396	3165	3435
ANOVA				$P > F$		
Rate		0.6087	0.6081	0.9854	0.4184	0.4869
Placement		0.0112	0.0519	0.8229	0.0361	0.4555
Rate*Placement		0.0622	0.0589	0.2071	0.6680	0.2835
CV (%)		15.86	9.69	8.40	14.00	11.50

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.14b Means of soybean seed yield in 2014 as affected by P fertilizer rate and placement.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		kg ha^{-1}				
-	0	3546	2127	2327	4047*a*	2099
Seed-Placed	-	3436	2541	2010	3577*a*	2292
Side-Band	-	3553	2392	-	-	-
Broadcast	-	3535	2481	2107	3992*a*	2147
-	0	3546	2127	2327	4047	2099
Seed-Placed	22.5	3547	2569	2035	3715	2059
	45	3486	2676	2125	3678	2083
	90	3276	2377	1872	3340	2303
Side-Band	22.5	3505	2227	-	-	-
	45	3523	2537	-	-	-
	90	3629	2411	-	-	-
Broadcast	22.5	3637	2335	2211	4096	2163
	45	3600	2464	2035	4000	2339
	90	3368	2644	2077	3879	2377
Mean		3512	2437	2097	3822	2203
ANOVA		$P > F$				
Rate		0.2776	0.4894	0.7155	0.3854	0.1535
Placement		0.3998	0.6144	0.5288	0.0313	0.1220
Rate*Placement		0.3213	0.6100	0.6852	0.8781	0.6773
CV (%)		7.57	16.39	23.95	12.09	11.10

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.15a Means of soybean seed yield in 2015 as affected by P fertilizer rate and placement.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015 kg ha^{-1}				
-	0	2995	2466	4405	3176	3172
Seed-Placed	22.5	2920	2315	-	3458	3470
	45	3322	2401	4372	3993	3286
	90	3417	2511	4887	3133	3393
Side-Band	22.5	3319	2426	4511	3832	3397
	45	3602	2513	4085	3671	3240
	90	3841	2420	4588	4443	3509
Broadcast	22.5	3059	2648	4664	4013	3296
	45	3337	2635	4582	3836	3344
	90	3122	2474	4741	3581	3298
Mean		3293	2481	4537	3714	3340
ANOVA		*P > F*				
Rate		0.1231	0.8350	0.0734	0.8983	0.0931
Placement		0.0674	0.1883	0.1967	0.1928	0.3283
Rate*Placement		0.8047	0.6198	0.7223	0.1181	0.1283
CV (%)		18.58	11.58	8.70	16.95	5.43

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.15b Means of soybean seed yield in 2015 as affected by P fertilizer rate and placement.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		kg ha^{-1}				
-	0	3096	2573*c*	3053	4338	3688
-	22.5	3204	2755*bc*	3037	4563	3830
-	45	3265	2919*ab*	2854	4632	3828
-	90	3432	3007*a*	2860	4533	3881
-	0	3096*a*	2573	3053*ab*	4338	3688
Seed-Placed	-	3493*a*	2883	2648*b*	4571	3857
Side-Band	-	3209*a*	2880	3108*a*	-	-
Broadcast	-	3200*a*	2918	3001*ab*	4581	3836
-	0	3089	2573	3053	4338	3688
Seed-Placed	22.5	3346	2764	3014	4579	3857
	45	3374	2936	2604	4552	3792
	90	3758	2949	2327	4582	3920
Side-Band	22.5	3214	2713	3053	-	-
	45	2974	2878	3052	-	-
	90	3439	3051	3201	-	-
Broadcast	22.5	3053	2788	3045	4547	3802
	45	3446	2944	2906	4711	3865
	90	3100	3021	3052	4485	3841
Mean		3279	2862	2931	4542	3824
ANOVA		*P* > *F*				
Rate		0.1833	0.0121	0.2424	0.8233	0.7800
Placement		0.0419	0.8707	0.0021	0.9420	0.7655
Rate*Placement		0.0751	0.9216	0.0834	0.7146	0.6299
CV (%)		10.98	11.95	14.63	7.12	4.78

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

The main concern of applying fertilizer with the seed is that some crops have low tolerance to the fertilizer's salt and therefore, plant emergence can be reduced. Side-banding is an efficient and safe way to place the fertilizer close to the seed, in the root zone, at planting. Phosphorus fertilizer placed in a subsurface band, when compared to broadcast, usually has increased efficiency because of the lower soil retention of P; moreover, the risk of P losses through water runoff is reduced when the fertilizer is banded below soil surface (Smith et al. 2016). However, banded fertilizer may have limited root access (Randall and Hoeft 1988). In the current study, there was no relationship between seed yield for the control versus side-banded fertilizer at a rate of 45 kg P_2O_5 ha^{-1} or broadcast P at a rate of 90 kg P_2O_5 ha^{-1} (Figure 2.1). However, side-banding was agronomically and environmentally safer, since seedling emergence was not compromised as in the seed-placed treatments and risk of P losses was not as great as in the broadcast treatments.

The fertilizer nitrogen applied with the monoammonium phosphate (11-52-0) varied according to the different rates of P applied and there was no compensation for it across treatments. Therefore, any yield response to the P fertilizer could also be attributed to the nitrogen present in the P fertilizer. However, satisfactory nodulation was observed at all sites. Therefore, we assume that biological nitrogen fixation provided most of the nitrogen taken up by the soybean and there was no positive or negative effect of the N added with the monoammonium phosphate.

Phosphorus fertilization effects on seed yield, either increases or decreases, had a poor relationship with mid-season dry matter yield, tissue P concentration and P uptake, except for Roseisle in 2015, where P rates increased plant tissue P concentration and seed yield. This site had the lowest whole plant tissue P concentration for the control (1.8 g kg^{-1}), demonstrating that concentrations below 2.0 g kg^{-1} could indicate P deficiency and a reasonable probability of a response to P fertilizer, even though two other sites also had plant tissue P concentrations below 2.0 g kg^{-1} and did not respond to P fertilization. Increased fertilizer rates resulted in greater mid-season biomass P concentration relative to the control in six site-years. However, the greater plant tissue P concentration had no nutritional benefit for seed yield in five of those six site years. This indicates that most of the increases in P concentration at mid-season were probably the result of luxury uptake, beyond the plants' nutritional requirement.

Seed-placed P at a rate of 22.5 kg P_2O_5 ha^{-1} can be considered a starter fertilizer, used to boost early season plant growth and, in some cases, seed yield. Seed-placed fertilizer at low rates has been proven to be beneficial for most crops in North America. This strategic placement allows plants to easily access P when soils are still cold during the spring, retarding P diffusion, and plant root and shoot growth (Grant et al. 2001). However, there was no overall trend for improved seed yields for seed-placed starter P relative to the control across a range of soil test P concentrations (Figure 2.1). In Manitoba, soybean is usually seeded in relatively warm soils, when soil temperature reaches at least 10° C. In addition, soybean seeds have large reserves of P, enough to supply the plant during this critical phase (Barber 1978), which may explain why no yield response to starter P was observed in our study or by Gervais (2009).

Due to the infrequency of seed yield increases to phosphorus fertilization, the establishment of a critical concentration range of soil P for soybean was not possible (Figure 2.1). Conversely, Mallarino and Dodd (2005) related the positive P responses obtained in their study to Bray-P_1 extractable P levels and therefore, established the critical concentration of P for soybean production in Iowa at 12 mg kg^{-1}, defined by a linear-plateau model. Nevertheless, in order to keep the soil P levels high enough to ensure reasonable yields for other crops in a rotation, the current critical soil P level in use for soybean production in Manitoba should be kept in the medium range (10 - 15 mg kg^{-1} Olsen extractable P).

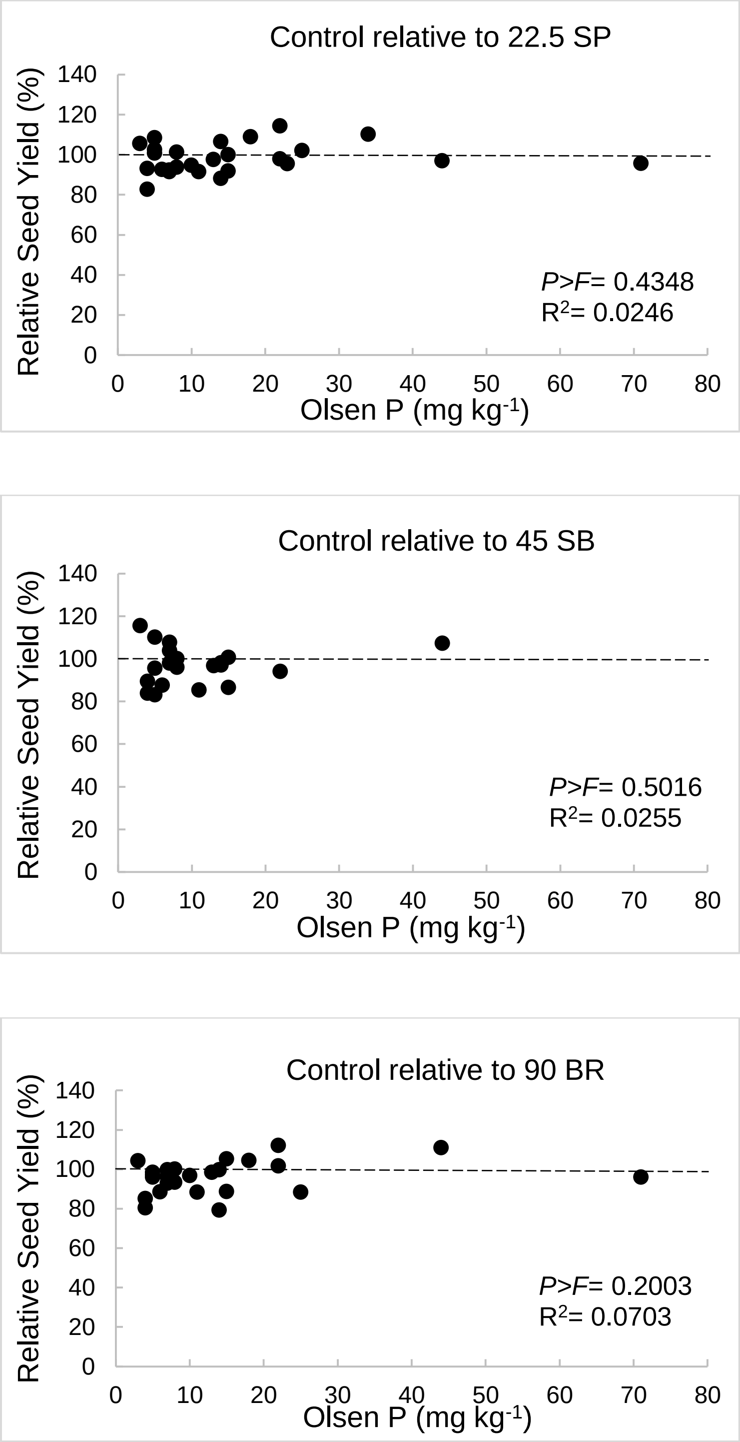

Figure 2.1 Relationships between soil test P and relative soybean seed yield defined as the yield for the control divided by the yield for the 22.5 kg P_2O_5 ha^{-1} seed-placed (22.5 SP), or 45 kg P_2O_5 ha^{-1} side-band (45 SP), or 90 kg P_2O_5 ha^{-1} broadcast (90 BR).

2.4.6. Seed P Concentration

Concentration of seed P was enhanced by P fertilization at 11 of the 28 site-years, but concentrations for fertilized treatments exceeded those for the control in only six of those site-years. There were seven site-years where the response was to P rate; four for placement and one for an interaction between P rate and placement.

In 2013, a significant interaction between rate and placement increased seed P concentration at 90 kg P_2O_5 ha^{-1} seed-placed in Melita, the same treatment that decreased seedling emergence and seed yield (Table 2.16a). The combination of a high rate of fertilizer P and the low yield resulted in a high concentration of P in the seeds. Also, the soil test P concentration at this site was extremely low (3 mg Olsen P kg^{-1}). In 2013 at Brandon, the rate of 90 kg P_2O_5 ha^{-1} enhanced seed P concentration compared to the other rates, similar to the observations for the biomass P concentration (Table 2.16a). Similarly, in 2014, Melita had higher seed P concentration for the rates of 90 and 45 kg P_2O_5 ha^{-1} relative to the control (Table 2.16a). Brandon in 2014 had increased P concentrations over the control for all the rates of P applied (Table 2.16b). At Beausejour in 2014, P concentrations for treatments of 90 kg P_2O_5 ha^{-1} were greater than for 22.5 kg P_2O_5 ha^{-1} (Table 2.16b). However, none of the P fertilized treatments at Beausejour had seed P concentrations greater than for the control. Therefore, this was probably a random error effect. In 2015, Brandon had seed P concentration increases over the control for 90 kg P_2O_5 ha^{-1}; Roseisle had increases for the rates of 90 and 45 kg P_2O_5 ha^{-1}, compared to the control; and at Roblin, the rate of 90 kg P_2O_5 ha^{-1} resulted in greater seed P concentration than the rate of 22.5 kg P_2O_5 ha^{-1}, but neither rate resulted in concentrations that were different from the control (Table 2.16b). In general, soil test P was in the low range of sufficiency (<10 mg kg^{-1}) where seed P concentration was enhanced by the fertilizer rates, similar to the observations for the mid-season plant tissue P concentration. However, P fertilization affected seed P concentration more frequently than biomass P concentration.

At Beausejour in 2013, where 45 kg P_2O_5 ha^{-1} broadcast lowered plant stand and biomass yield, the broadcast and seed-placed fertilizer treatments had greater seed P concentration than the side-band treatments (Table 2.16a). The site at St. Adolphe in 2013 had greater P concentration for the broadcast treatments than the seed-placed fertilizer. This effect appeared to be a random error since there was no treatment effect on other parameters analysed, such as plant stand and biomass P concentration (Table 2.16a). At Carman in 2014, the seed-placed fertilizer increased seed P concentration compared to the side-band treatments, which appeared to be a random effect, as well, given the lack of effects on other parameters, such as plant stand, biomass and seed yield (Table 2.16a). At Roblin in 2015, there was a significant increase for seed P concentration in the seed-placed treatments compared to the side-band treatments, which conformed to the plant stand reduction observed at 90 kg P_2O_5 ha^{-1} in the seedrow, resulting in more P available to the remaining plants (Table 2.16b).

Table 2.16a Sites with significant effects of P fertilization on seed P concentration.

Treatment		Melita	Brandon	Beausejour	St. Adolphe	Carman	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013	2013	2013	2013	2014	2014
		Seed P concentration (mg kg^{-1})					
-	0	5.0	4.4*c*	5.1*a*	5.3	4.7	3.9*c*
-	22.5	5.3	4.9*bc*	4.9*a*	5.4	4.7	4.2*c*
-	45	5.3	5.1*b*	5.2*a*	5.5	4.7	4.6*b*
-	90	5.6	5.6*a*	5.3*a*	-	4.9	4.9*a*
-	0	5.0	4.4	5.1*ab*	5.3*ab*	4.7*ab*	3.9
Seed-Placed	-	5.6	5.1	5.2*a*	5.2*b*	5.0*a*	4.5
Side-Band	-	5.3	5.3	5.0*b*	-	4.7*b*	4.7
Broadcast	-	5.3	5.1	5.2*a*	5.6*a*	4.8*ab*	4.6
-	0	5.0*b*	4.4	5.0	5.3	4.7	3.8
Seed-Placed	22.5	5.3*b*	4.9	4.9	5.1	4.7	4.1
	45	5.2*b*	4.8	5.2	5.3	5.0	4.4
	90	6.2*a*	5.6	5.4	-	5.1	4.8
Side-Band	22.5	5.2*b*	4.9	4.8	-	4.8	4.2
	45	5.2*b*	5.3	5.1	-	4.5	4.6
	90	5.3*b*	5.7	5.0	-	4.7	5.3
Broadcast	22.5	5.3*b*	4.8	4.9	5.6	4.7	4.4
	45	5.4*b*	5.0	5.4	5.6	4.7	4.6
	90	5.3*b*	5.6	5.4	-	4.9	4.7
Mean		5.3	5.1	5.1	5.4	4.8	4.5
ANOVA		$P > F$					
Rate		0.012	0.0002	0.0446	0.5337	0.0763	<.0001
Placement		0.0576	0.3729	0.006	0.0106	0.0150	0.1060
Rate*Placement		0.008	0.7366	0.2161	0.7883	0.1797	0.0919
CV (%)		7.02	10.92	6.38	5.89	6.30	10.44

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.16b Sites with significant effects of P fertilization on seed P concentration.

Treatment		Brandon	Beausejour	Brandon	Roblin	Roseisle
Placement	Rate (kg P_2O_5 ha^{-1})	2014	2014	2015	2015	2015
		Seed P concentration (mg kg^{-1})				
-	0	4.2*c*	4.1*ab*	4.1*b*	5.5*ab*	3.2*c*
-	22.5	4.8*b*	4.1*b*	4.1*b*	5.2*b*	3.7*bc*
-	45	4.8*ab*	4.3*ab*	4.4*ab*	5.3*b*	4.0*b*
-	90	5.2*a*	4.4*a*	4.8*a*	5.6*a*	4.4*a*
-	0	4.2	4.1	4.1	5.5*ab*	3.2
Seed-Placed	-	4.9	4.3	4.4	5.6*a*	4.2
Side-Band	-	5.0	4.2	4.4	5.2*b*	3.9
Broadcast	-	4.9	4.2	4.5	5.3*ab*	4.0
-	0	4.2	4.1	4.1	5.5	3.2
Seed-Placed	22.5	4.6	4.0	4.1	5.4	4.0
	45	4.8	4.5	4.3	5.4	3.9
	90	5.3	4.5	4.9	5.9	4.7
Side-Band	22.5	4.9	4.2	4.2	4.9	3.4
	45	4.8	4.1	4.2	5.2	4.1
	90	5.3	4.3	4.8	5.6	4.2
Broadcast	22.5	4.7	4.0	4.1	5.2	3.8
	45	4.9	4.3	4.5	5.3	3.8
	90	4.9	4.3	4.9	5.4	4.3
Mean		4.8	4.2	4.4	5.4	3.9
ANOVA		$P > F$				
Rate		0.0056	0.0119	0.0121	0.0008	<.0001
Placement		0.4503	0.2637	0.5559	0.0139	0.1158
Rate*Placement		0.3947	0.1997	0.7161	0.4386	0.2068
CV (%)		9.53	8.03	12.69	6.66	12.87

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

2.4.7. Seed P Uptake

Seed P uptake, which is calculated by the combination of seed P concentration and seed yield, was significantly affected by P fertilization at 7 of 28 site-years. However, P fertilizer treatments resulted in seed P uptake differences compared to the control in only 5 of the 7 responsive site-years. Seed P uptake was reduced by 90 kg seed-placed P_2O_5 ha^{-1}, compared to the control at Carberry in 2013 (Table 2.17). This high rate of seedrow P reduced plant stand and seed yield, and because there was no increase in seed P concentration, the seed P uptake were reduced relative to the control, as well. Conversely, at Melita in 2013, despite the reduced plant stand and seed yield at 90 kg P_2O_5 ha^{-1} seed-placed, seed P concentration was significantly increased at this treatment, resulting in no effect on seed P uptake. The treatment of 90 kg P_2O_5 ha^{-1} broadcast increased seed P uptake compared to the control at Brandon in 2013, where biomass and seed P concentration was also enhanced by high rates of P (Table 2.17).

Greater P uptake for the side-band treatments compared to the control was observed at Brandon in 2014, which is supported by the results observed for biomass P uptake and seed P concentration (Table 2.17).

At Carman in 2015, seed-placed P had more P uptake compared to the broadcast treatments but it did not concur with the observations for biomass P concentration and thus, it was probably a random error effect (Table 2.17). The opposite occurred at Arborg in 2015, where greater seed P uptake was observed for the broadcast compared to the seed-placed. The sites at Brandon and Roseisle 2015 had greater seed P uptake at 90 and 45 kg P_2O_5 ha^{-1}, and 90 kg P_2O_5 ha^{-1}, respectively, relative to the control, reinforcing the observations for seed and biomass P concentration (Table 2.17). The significant ANOVA *P* value observed for rate at Carman in 2015 was not reflected in the Tukey-Kramer test, resulting in no differences between the means groupings.

Overall, seed P uptake was poorly related to plant tissue and seed P concentration, biomass yield and seed yield. Phosphorus removal per tonne of grain produced, ranged from 3.2 to 7.1 kg, with overall average of 5.2 kg. This average value is similar to the P removal suggested by the Manitoba Soil Fertility Guide, which is 6.2 kg per tonne of grain (MAFRD 2007).

Table 2.17 Sites with significant effects of P fertilization on seed P uptake.

Treatment		Carberry	Brandon	Brandon	Brandon	Arborg	Carman	Roseisle
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2013	2013	2014	2015	2015	2015	2015
		Seed P uptake ($kg\ ha^{-1}$)						
-	0	23.6	10.4	4.8	12.5*b*	16.2	12.9*a*	8.2*c*
-	22.5	22.9	10.8	6.0	12.9*b*	15.7	13.0*a*	10.2*bc*
-	45	22.4	11.1	6.2	14.9*ab*	16.3	13.2*a*	11.5*b*
-	90	20.2	11.3	6.3	17.1*a*	16.2	14.8*a*	13.3*a*
-	0	23.6	10.4	4.8*c*	12.5	16.2*ab*	12.9*ab*	8.2
Seed-Placed	-	21.0	10.5	5.6*bc*	14.6	15.4*b*	15.2*a*	12.1
Side-Band	-	22.1	10.8	6.8*a*	15.9	15.9*ab*	13.0*ab*	11.3
Broadcast	-	22.3	11.9	6.1*ab*	14.4	17.0*a*	12.8*b*	11.6
-	0	23.6*a*	10.4*b*	4.8	12.5	16.2	12.9	8.2
Seed-Placed	22.5	24.6*a*	10.4*b*	5.9	12.0	14.8	14.9	11.0
	45	21.2*ab*	10.9*b*	5.9	14.3	15.4	14.0	11.5
	90	17.8*b*	10.2*b*	5.1	17.8	15.9	16.5	13.8
Side-Band	22.5	22.8*a*	10.8*b*	6.6	14.1	15.5	12.0	9.2
	45	22.2*ab*	11.3*ab*	6.5	15.3	16.0	12.5	11.8
	90	21.4*ab*	10.5*b*	7.3	18.5	16.0	14.4	12.9
Broadcast	22.5	21.4*ab*	11.3*ab*	5.6	12.7	16.8	11.9	10.5
	45	23.8*a*	11.2*b*	6.2	15.2	17.6	13.1	11.3
	90	21.7*ab*	13.2*a*	6.5	15.2	16.7	13.5	13.1
Mean		22.0	11.0	6.0	14.7	16.1	13.6	11.3
ANOVA		$P > F$						
Rate		0.0407	0.3845	0.6778	0.0019	0.5256	0.0134	<.0001
Placement		0.2952	0.0009	0.0034	0.2574	0.0197	0.0010	0.3233
Rate*Placement		0.0242	0.0098	0.1525	0.6214	0.8711	0.5828	0.5850
CV (%)		20.25	10.18	16.95	26.71	12.87	14.15	20.12

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

2.4.8. Seed Protein Concentration

Protein content of the seeds was generally unaffected by P fertilization (Appendix H). At Arborg in 2013, the rate of 90 kg P_2O_5 ha^{-1} produced greater protein concentration (320 g kg^{-1}) than 45 kg P_2O_5 ha^{-1} (297 g kg^{-1}) but was not different from the control. However, at Arborg in 2014, protein content was significantly greater for the control (347 g kg^{-1}) compared to 90 kg P_2O_5 ha^{-1} broadcast (337 g kg^{-1}). At Carberry in 2015, 22.5 kg P_2O_5 ha^{-1} seed-placed (347 g kg^{-1}) produced a higher concentration of protein than 90 kg P_2O_5 ha^{-1} seed-placed (340 g kg^{-1}) but was not different from the control (343 g kg^{-1}). At Brandon and Roblin in 2015, the significant ANOVA *P* values were not detected by the Tukey-Kramer analysis. None of these fertilizer treatment effects were associated with other parameters such as plant tissue and seed P concentration. Therefore, these differences were likely random.

2.4.9. Seed Oil Concentration

Seed oil concentration was poorly related to biomass and seed P concentration and uptake, and only one of the fertilized treatments was different from the control (Appendix I). Therefore, these differences were probably random error effects, as well. Side-band treatments (187.5 g kg^{-1}) improved oil content compared to the seed-placed treatments (184.3 g kg^{-1}) at Arborg in 2013. The significant rate effect at this site was not reflected by the Tukey-Kramer test. Side-band treatments (157.0 g kg^{-1}) increased oil concentration compared to the control (152.7 g kg^{-1}) at Carberry in 2014. At Brandon in 2013, oil concentration was greater at the rate of 22.5 kg P_2O_5 ha^{-1} (144.8 g kg^{-1}) compared to the 90 kg P_2O_5 ha^{-1} (142.4 g kg^{-1}) and at St Adolphe in 2015, 22.5 kg P_2O_5 ha^{-1} (176.2 g kg^{-1}) produced greater seed oil concentration than 45 kg P_2O_5 ha^{-1} treatments (172.6 g kg^{-1}), respectively.

The linear and inverse relationship for protein and oil concentration had an R^2 of 0.5593 and $P>F$ of 0.0001, which were similar to the observations of Mallarino and Haq

(2005), who reported that protein and oil concentration relate inversely to each other; as the oil content increases the protein content decreases and vice versa. In this study, protein and oil concentration were not related to the effects of P fertilization on seed yield or plant tissue and seed P concentrations, similar to the observations by Mallarino and Haq (2005), as well.

2.4.10. 1000 Seed Weight

Seed size or 1000 seed weight, is complementary to seed yield measurement, since bigger seeds will result in greater yield if the number of seeds compared is similar. In this study, seed size had a poor relationship with the previous described parameters in this chapter, including seed yield, and was poorly explained by the fertilizer treatments (Tables 2.18a and 2.18b), similar to the findings of Fernandez (2012). Only at Roseisle in 2015, seed yield and seed size were increased simultaneously by P fertilization.

In 2013, Portage had increased seed size for the seed-placed treatments compared to broadcast (Table 2.18a). However, there was no evidence in any other parameters to account for this placement effect. In 2014, Arborg had somewhat similar results, where seed size for seed-placed P was greater than for side-banded P, but there was no other indication for that such as increased P concentration or uptake (Table 2.18a). Conversely, in 2014, Carberry had reduced seed size for the seed-placed fertilizer treatments compared to the side-band and broadcast treatments, and this difference is supported by the lower plant tissue P uptake for the seed-placed treatments and the plant stand reduction caused by 45 and 90 kg P_2O_5 ha^{-1} seed-placed

(Table 2.18a). The rates of 45 and 90 kg P_2O_5 ha^{-1} increased seed size compared to the control in Brandon in 2014, what could be the result of the greater seed P concentration for the same treatments (Table 2.18a). Seed-placed fertilizer increased seed size at Roblin in 2014, relative to the broadcast and control treatments but these effects were not observed in any of the other parameters analysed for this location (Table 2.18a).

In 2015, Arborg had greater seed size for the seed-placed fertilizer, compared to the broadcast placement. However, these results are the opposite of those observed for seed P uptake, where uptake from the broadcast placement was greater (Table 2.18b). At Carberry in 2015, seed size for side-banded P was greater than for the seed-placed treatments, and at St. Adolphe in 2015, 45 kg P_2O_5 ha^{-1} seed-placed produced larger seeds than 45 kg P_2O_5 ha^{-1} broadcast (Table 2.18b), which again seems to be a random effect as it is not easily explained by the fertilizer treatment. The significant seed yield increase observed at Roseisle at 2015 could be related to the larger seeds produced at the rates of 90 and 45 kg P_2O_5 ha^{-1}, compared to the control (Table 2.18b).

Table 2.18a Sites in 2013 and 2014 with significant effects of P fertilization on 1000 seed weight.

Treatment		Portage	Arborg	Carberry	Brandon	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2013	2014	2014	2014	2014
		1000 seed weight (g)				
-	0	160.3	176.2	142.8	166.7*c*	144.0
-	22.5	170.3	175.6	145.4	172.0*bc*	147.8
-	45	164.3	176.3	145.1	173.5*ab*	147.5
-	90	-	173.1	143.1	177.2*a*	146.2
-	0	160.3*ab*	176.2*ab*	142.8*ab*	166.7	144.0*b*
Seed-Placed	-	176.7*a*	177.8*a*	139.8*b*	174.3	148.8*a*
Side-Band	-	-	172.3*b*	147.6*a*	175.1	-
Broadcast	-	158.4*b*	174.9*ab*	146.3*a*	173.3	145.6*b*
-	0	160.3	176.2	142.8	166.7	144.0
Seed-Placed	22.5	181.6	178.0	143.0	170.4	148.8
	45	171.8	182.3	139.1	173.5	149.0
	90	-	173.3	137.3	179.0	148.6
Side-Band	22.5	-	173.2	147.6	173.8	-
	45	-	173.1	149.4	173.3	-
	90	-	170.6	145.8	178.3	-
Broadcast	22.5	159.6	175.7	145.5	171.7	146.7
	45	157.1	173.6	147.0	173.8	146.1
	90	-	175.3	146.4	174.2	144.0
Mean		166.1	175.1	144.4	173.5	146.7
ANOVA		$P > F$				
Rate		0.3153	0.2100	0.3188	0.0162	0.6023
Placement		0.0073	0.0234	<.0001	0.5603	0.0251
Rate*Placement		0.5678	0.2832	0.3975	0.5365	0.7312
CV (%)		10.42	3.25	3.49	2.93	3.23

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table 2.18b Sites in 2015 with significant effects of P fertilization on 1000 seed weight.

Treatment		Arborg	Carberry	Roseisle	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015	2015	2015	2015
		1000 seed weight (g)			
-	0	170.6	160.8	166.0*b*	167.0
-	22.5	174.5	158.9	168.8*b*	162.2
-	45	171.6	159.0	175.0*a*	167.4
-	90	170.4	160.3	174.6*a*	164.6
-	0	170.6*ab*	160.8*ab*	166.0	167.0
Seed-Placed	-	174.7*a*	157.3*b*	172.9	167.8
Side-Band	-	171.9*ab*	161.2*a*	172.2	-
Broadcast	-	169.9*b*	159.7*ab*	173.3	161.7
-	0	170.6	160.8	166.0	167.0*ab*
Seed-Placed	22.5	179.0	155.9	170.3	162.1*b*
	45	174.7	159.3	175.8	174.6*a*
	90	170.3	156.7	172.6	166.9*ab*
Side-Band	22.5	174.7	160.5	166.8	-
	45	170.2	160.2	173.6	-
	90	170.9	162.8	176.4	-
Broadcast	22.5	169.7	160.1	169.3	162.2*b*
	45	169.9	157.4	175.8	160.6*b*
	90	170.0	161.5	174.8	162.4*b*
Mean		172.0	159.5	172.1	165.1
ANOVA		$P > F$			
Rate		0.0588	0.3671	0.0044	0.1168
Placement		0.0267	0.0075	0.8505	0.0054
Rate*Placement		0.2561	0.1306	0.6046	0.0267
CV (%)		3.5	2.38	5.9	3.83

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

2.5. Conclusions

Plant stand was rarely affected by monoammonium phosphate (MAP) fertilizer placed with the seed. Only five site-years had plant stand reductions and these were generally caused by high rates of MAP applied in the seedrow, especially in the medium to coarse textured soils and/or if the seeding equipment had low soil disturbance and seed bed utilization. Therefore, in this study, soybean appeared to tolerate greater rates of seed-placed fertilizer than what is currently recommended. However, we cannot assume that higher rates of P applied with seed will always be safe because there are many factors affecting fertilizer toxicity, including precipitation and soil moisture, which were generally satisfactory during the years of this study.

Mid-season biomass was not enhanced by phosphorus fertilization in any site-year regardless of phosphorus fertilizer rate, placement, and soil P levels. Only two site years showed significant reduction, but this effect could not be attributed to the fertilizer treatments. Mid-season biomass yield was not affected by the reduced plant emergence in sites where seed-placed fertilizer significantly reduced plant stand, in part, because of the compensatory growth of the soybean plants.

Seed yield increase by P fertilization was rare and occurred at only one of 28 site-years, at rates of 45 and 90 kg P_2O_5 ha^{-1}. However, seed yield was decreased at two site years when plant stand was reduced below 247,000 plants ha^{-1}, as a consequence of the severe toxicity caused by the high rates of P fertilizer placed close to the seed.

Phosphorus concentrations in plant tissue and seed were enhanced by P fertilization at eight and six site-years, respectively, compared to the control. The increases in P concentration generally occurred in low soil P sites (< 10 mg kg $^{-1}$ Olsen P), but had no nutritional benefits as they were poorly related to biomass yield, seed yield, protein concentration, oil concentration and 1000 seed weight. However, the lowest plant tissue P concentration, 1.8 g kg^{-1}, was observed for the control in the only responsive site-year in this study, which was Roseisle in 2015.

There was no consistent effect of fertilizer treatment on seed protein and oil concentration. Furthermore, P fertilization for increasing protein and oil concentration is commercially irrelevant since soybean growers are not compensated for these quality parameters. Since there was generally no seed yield increase from P fertilization, the treatment effects on 1000 seed weight had little influence on yield and did not relate to phosphorus concentration in biomass and seed, except at the one site-year where a seed yield response to P fertilizer was measured.

Even though soybean seed yield did not generally increase due to phosphorus fertilization, phosphorus removal with seed harvesting is substantial and should be considered in a soil P budget (P input – P output). Nevertheless, P removal can be replenished in other phases of the crop rotation, in order to maintain soil P fertility.

3. RESPONSE OF SOYBEAN TO SOIL PHOSPHORUS FERTILITY IN MANITOBA

Keywords: soybean (*Glycine max* (L.) Merr**,** phosphorus fertility, soil test phosphorus, seed yield

3.1. Abstract

Recent work has showed that soybean rarely has yield increases to P fertilization but have high removals of P with seed harvesting, indicating that soil P may be the preferred source of P used by soybean. In order to evaluate the response of soybean to soil P fertility, a field study was conducted over seven site-years at three locations in Manitoba during 2013, 2014 and 2015. The sites for this study had been used for a previous long term study, in which different rates of monoammonium phosphate (11-52-0) were annually applied to the same plots for a period of nine years creating a large range of soil P levels. Soybean was grown on these plots which had a range of background soil P varying from 7 to 93 mg kg^{-1} Olsen extractable P. There were no seed yield increases in response to soil test P concentrations at any site. Yield increases reported by producers in soils with high soil test P might be due to other factors, such as high soil fertility overall, not only for P.

3.2. Introduction

Soybean (*Glycine max* (L.) Merr) production in Manitoba has increased substantially during the last decade. Seeded area reached 560,729 ha in 2015 (Statistics Canada 2016), driven by modern, short growing season varieties and low input costs, after considering savings in the cost of nitrogen fertilizer. Growing soybean without any fertilizer is a common practice in Manitoba. Synthetic nitrogen is dispensable because of the efficient nitrogen supply through the biological nitrogen fixation and phosphorus (P) is usually not applied, since growers are not confident that there is a seed yield benefit to phosphorus fertilization. Therefore, many of the producers do not apply any fertilizer to the soybean crop.

Reports about soil P levels in Manitoba have indicated that soil P is declining across the province. Fixen et al. (2010) reported that 57% of the soil analyses for P in Manitoba were classified in the low levels of sufficiency. In 2016, 64% of the soil samples tested for P were in the low range of sufficiency (IPNI 2016), an increase of 7%. Coincidentally, as the soybean production areas are expanding, more fields are testing low for soil P concentration. The decline in soil P levels can be attributed to the lack of fertilization for soybean and to the displacement in seeded areas of crops that have low removal of P, such as barley (*Hordeum vulgare*) and oats (*Avena sativa*), by soybean. Furthermore, although canola (*Brassica napus*) and wheat (*Triticum aestivum*) are fertilized with P, the rates may not be sufficient to replace P removal with grain harvest of modern, high yielding varieties of these crops.

The absence of phosphorus fertilization for soybean is supported by the fact that yield responses of soybean to P fertilizer are not reliable. Gervais (2009) observed no yield increase to P fertilization in Manitoba. Soybean removes substantial amounts of phosphorus with seed harvesting, which consist of approximately 6.2 kg of P removed per tonne of seed harvested (Manitoba Agriculture Food and Rural Development (MAFRD) 2007). The lack of response to P fertilizer and the high removal by the crop indicates that soybean often relies on soil P reserves for crop nutrition. Kalra and Soper (1968) observed that P uptake from phosphorus fertilizer by soybean, rape, oats and flax were similar; however, soybean absorbed greater amounts of P from soil reserves than the other crops.

A combination of phosphorus fertilization in addition to good soil fertility may be the key for reaching high yields. Several studies have shown that when grown on high P fertility soils, soybean can produce greater yields than when grown on low P soils. Randall (2012) observed greater soybean yield at high soil test P than at low soil test P. Mallarino and Dodd (2005) also observed frequent response to P fertilizer in low soil test P but there was no yield increase to P fertilization in high soil test P. Responses to soil test P were less frequent than for added P fertilizer, and only occurred when plots were in the low critical level of sufficiency. Blackmer et al. (1992) also observed yield increase to P fertilization on low soils test P. However, there was no yield response to different levels of soil P. In sites with high soil P levels, significant yield response to fertilizer was observed at a maximum rate of 11 kg P ha^{-1}, which indicates that in high soil test P, a starter rate of P may be sufficient to increase soybean yield.

The purpose of the current study was to investigate the seed yield response of soybean to different background of soil test P concentrations in Manitoba.

Materials and Methods

3.2.1. Experimental Sites and Treatments

During 2013, 2014 and 2015, seven site-years of field studies were conducted at Brandon, Forrest and Carman, in Manitoba. A previous long term experiment established in 2002 was used as the base for this study. These three sites were the remainder of long term trials that had been established in Manitoba, Saskatchewan and Alberta, to evaluate the long term effects of different rates of phosphorus fertilizer containing different concentrations of cadmium on crop production (Grant et al. 2013). Cadmium content in food and feed is a health safety concern, which became regulated by the Codex Alimentarius established by the World Health Organization. From 2002 to 2009, monoammonium phosphate fertilizer was applied at 20, 40 and 80 kg P ha^{-1}, using three phosphate sources, containing either low (0.4 mg kg^{-1}), medium (70 mg kg^{-1}) or high (210 mg kg^{-1}) concentrations of Cd. The treatments also included an unfertilized control. During this eight year period, the P treatments were applied annually to the same plots, creating a diverse range of soil P levels over the plots, which were used in the current study. From 2010 to 2013, P fertilizer was not applied. In 2013, 2014 and 2015, soybean was seeded on the long term trials previously established at Brandon, Forrest and Carman.

Treatments established in 2002 for the long term trials included:

1) Control
2) 20 kg P ha^{-1} and low Cd
3) 40 kg P ha^{-1} and low Cd
4) 80 kg P ha^{-1} and low Cd
5) 20 kg P ha^{-1} and Medium Cd
6) 40 kg P ha^{-1} and Medium Cd
7) 80 kg P ha^{-1} and Medium Cd
8) 20 kg P ha^{-1} and High Cd
9) 40 kg P ha^{-1} and High Cd
10) 80 kg P ha^{-1} and High Cd

3.2.2. Statistical Design

Statistical analyses were conducted with the Glimmix procedure of SAS 9.4 (SAS Institute, Inc. 2016). Conformity of the data was analysed with the Univariate procedure using the Shapiro-Wilk test. Means separation between treatments were determined according to the Tukey - Kramer method with probability level for significance of 0.05.

Trials were set up in a Randomized Complete Block experimental design. The long term trial previously established was arranged in a two-way factorial treatment design (P rate x Cd level) plus a control. Plots were replicated four times. Block was treated as a random effect and P rates and Cd levels were considered the fixed effects. Statistical analyses were designed to consider the factorial composition of the experiment, in combination with the control treatment.

3.2.3. Seed Treatment and Weed control

The variety of soybean grown was Dekalb 24-10 RY with a plant population target of 518,700 plants per hectare. Seeds were treated with fungicide, insecticide and liquid inoculant for biological nitrogen fixation (*Bradyrhizobium japonicum*), prior to seeding. Seed treatment in 2013 and 2014 consisted of CruiserMaxx Vibrance, which contains thiamethoxam insecticide and metalaxyl, fludioxonil and sedaxane fungicides. In 2015, seeds were treated with Acceleron seed treatment which contains fluxapyroxad, pyraclostrobin and metalaxyl fungicides and imidacloprid insecticide, in addition to Optimize liquid inoculant. Regardless of the seed treatment, granular inoculant (*Bradyrhizobium japonicum*) was applied to all the plots, in furrow, at the rate of 20 kg ha^{-1}.

Weeds were controlled when required with two glyphosate (540 g a.i. L^{-1}) applications at the rate of 1.6 L ha^{-1}.

3.2.4. Mid-Season Biomass

Plants were sampled at R3 growth stage (beginning pod) in order to characterize the phosphorus nutrition of the plants, Cd uptake and dry matter yield. Plants were harvested in two rows, one metre length, on the plot side that did not receive starter P. Plants were cut at ground level, oven dried at 60° C and weighed.

3.2.5. Seed Yield and Biomass

Plots were harvested using a plot combine and a sample of the soybean crop residue was taken for analyses of plant P and Cd concentrations, uptake and biomass accumulation at crop maturity. Seed moisture was determined at harvest and all measurements were converted to 130 g kg^{-1} moisture basis.

3.2.6. Soil Sampling and Analyses

Soil samples were taken in each plot during the fall of 2013, 2014 and 2015, at 0 - 7.5 and 7.5 - 15 cm depth. Samples were composed of 10 subsamples, randomly taken in each plot. Soil samples were air dried and ground with a soil pulverizer. Standard chemical analyses were conducted in the Agriculture and Agri-Food Canada in Brandon, in order to characterize the soil nutrients and Cd concentrations. Nitrate-N and P were extracted with sodium bicarbonate, sulphur (S) with $CaCl_2$, zinc (Zn) and Cd with DTPA. Nitrate concentration was determined colorimetrically; S, Zn and P detetermined by inductively coupled plasma spectroscopy; and Cd by atomic absorption spectrophotometry (Grant et al. 2013).

3.2.7. Plant Tissue Analyses

Mid-season biomass and post-harvest biomass samples were ground using a Thomas - Wiley Mill Grinder, with a two millimetre screen, and analysed by the Agriculture and Agri-Food Canada laboratory at Brandon, MB.

3.2.8. Site Characteristics

Trials were located near Carman – MB (49° 29.7’ N, 98° 2.4’ W), Brandon – MB (49° 52.0’N, 99° 58.3’W) and Forrest – MB (50° 1.2’ N, 99° 53.3’ W) which had loamy, silt clay loam and clay loam soil texture, respectively, as described by Grant et al. (2013). At Carman, the soil was an Orthic Black Chernozem with loam texture, at Brandon, an Orthic Black Chernozem with silt clay loam texture and at Forrest, a

Gleyed Cumulic Regosol with clay loam texture. More information about the soils at each site is provided in Appendix L.

Table 3.1 Cumulative precipitation by location and year, from May to September.

Location	2013	2014	2015
		(mm)	
Brandon	383	503	250
Carman	307	364	373
Forrest	389	440	270

Data retrieved from Manitoba Agriculture, Food and Rural Development website.

3.2.9. Soil Phosphorus

Initial soil P levels before the initial applications of P in 2002 were 24, 13 and 22 mg kg^{-1} for Carman, Forrest and Brandon, respectively (Grant et al. 2013). After eight years of fertilizer P and Cd loadings at different rates in the same plot every year and annual crop growth and harvest, a broad gradient of soil P levels was created. In 2013, Olsen soil test P concentrations ranged from 6.8 to 93.1 mg kg^{-1}, and soil pH varied from 5.1 to 7.8 (Table 3.2).

Table 3.2 Means of Olsen soil test P at the start of this study, in 2013, after the historical annual application of fertilizer P from 2002 to 2009.

Treatment		Forrest	Brandon	Carman
Historical annual P (kg ha^{-1})^{y}	Fertilizer Cd concentration		mg kg^{-1}	
0	-	6.8	10.8	19.6
20	Low	14.0	22.1	32.2
	Medium	15.2	20.2	27.9
	High	15.3	24.2	32.6
40	Low	22.4	32.1	51.3
	Medium	22.3	35.5	52.4
	High	22.4	32.6	54.2
80	Low	34.2	49.8	90.2
	Medium	45.1	54.5	90.6
	High	41.1	57.2	93.1

3.3. Results and Discussion

3.3.1. Seed Yield

Seed yield averages for the trials established in 2013, 2014 and 2015 were 3131, 3076 and 2809 kg ha^{-1}, respectively. These average yields were greater than the 2013, 2014 and 2015 provincial averages of 2587, 2243 and 2580 kg ha^{-1}, respectively (Manitoba Agricultural Services Corporation 2016), due in part to the reasonable amounts of growing season precipitation at the sites (Table 3.1).

Seed yield was not increased at any site-year by the historic phosphorus treatments, which created the variable range of soil test P concentrations (Table 3.2) in this study, except for Carman in 2014, where there was a significant interaction between P rate and Cd level, in which the 40 kg P ha^{-1} containing low Cd had greater yield than the treatment of 80 kg P ha^{-1} containing low Cd (Tables 3.3 and 3.4). However, these treatments were not different from the control. In other words, high soil test P did not increase seed yield, compared to the control treatment, which never received P fertilizer throughout the current or previous experiment. Our results are different from those of some other studies in North America, in which soybean responded to soil P fertility (Randall 2012; Lauzon and Miller 2008; Sabbe et al. 1996; Touchton and Rickerl 1986).

Cadmium loadings did not increase or decrease seed yield, which was expected, since Cd is not a nutrient (Tables 3.3 and 3.4). The main concern about Cd is that the high concentrations in the seed are not safe for human consumption.

Table 3.3 Seed yields for the trials established in 2013 and 2014, as affected by historical P rate and cadmium concentration in the P fertilizer.

Treatment		Brandon 2013	Forrest 2013	Carman 2014	Forrest 2014
Historical annual P (kg ha^{-1})^{y}	Fertilizer Cd concentration	(kg ha^{-1})^{z}			
0	-	3605	2977	3796*ab*	2386
20	-	3262	2847	3866*ab*	2356
40	-	3377	2982	4073*a*	2320
80	-	3392	2815	3627*b*	2197
0	-	3605	2977	3796	2386
20	Low	3265	2880	3759	2324
	Medium	3313	2845	4093	2410
	High	3207	2817	3747	2335
40	Low	3419	3094	4310	2262
	Medium	3456	2804	3919	2328
	High	3257	3048	3991	2371
80	Low	3218	2976	3516	2078
	Medium	3426	2943	3728	2392
	High	3530	2526	3638	2119
Mean		3370	2891	3850	2301
ANOVA		$P > F$			
P rate		0.6719	0.4812	0.0208	0.1615
Cd level		0.8216	0.4386	0.7191	0.1976
P rate*Cd Level		0.7931	0.4348	0.3205	0.5839
CV (%)		13.10	12.15	12.79	9.29

[z] Means followed by the same letter grouping are not significantly different at $P < 0.05$.

[y] Rates of P applied yearly from 2002 to 2009

Table 3.4 Seed yields for the trials established in 2015, as affected by historical P rate and cadmium concentration in the phosphorus fertilizer.

Treatment		Brandon	Forrest	Carman
Historical annual P (kg ha^{-1})^{y}	Fertilizer Cd concentration	Seed Yield (kg ha^{-1})^{z}		
0	-	2106	2882	3352
20	-	2100	2710	3615
40	-	2187	2866	3597
80	-	2122	2805	3309
0		2106	2882	3352
20	Low	1734	2690	3996
	Medium	2148	2738	3311
	High	2417	2701	3537
40	Low	2214	2874	3300
	Medium	2014	2970	3691
	High	2332	2754	3800
80	Low	2334	2951	3689
	Medium	1871	2674	3011
	High	2161	2782	3227
Mean		2133	2802	3491
ANOVA		*P > F*		
P Rate		0.8674	0.5077	0.3738
Cd Level		0.2214	0.8045	0.4123
P rate*Cd Level		0.2206	0.7541	0.2797
CV (%)		19.57	16.85	16.97

[z] Means followed by the same letter grouping are not significantly different at $P < 0.05$.

[y] Rates of P applied yearly from 2002 to 2009.

3.4. Conclusions

There was no seed yield increase relative to the control treatment, regardless of background concentrations of soil P and Cd loadings. Observations that soil P fertility increases seed yield in producer`s fields are likely to be due to high soil fertility, including other plant nutrients, or history of manure application.

4. OVERALL SYNTHESIS

4.1. Summary

Soybean has become a major crop in Manitoba and still requires research for this specific production area. Phosphorus fertilization is an important issue to be studied because every year, farmers designate a large portion of their costs of production to purchasing phosphorus fertilizer, and improper fertilization can result in lost yields, depletion of soil P levels, injury to crop establishment or losses through water runoff and erosion, causing substantial problems to fresh water bodies due to eutrophication.

A typical P fertilization practice in Manitoba is the application of the P fertilizer with the seed, which is limited by the amount of P that can be applied safely because fertilizer toxicity can damage crop establishment. Therefore, one objective of the first study, reported in Chapter 2, was to identify the safe rates of P fertilizer applied with the seed. The current guidelines limit the rate of P applied with the seed to 11 kg ha^{-1} for row spacings below 15 cm, only. This rate of fertilizer is very low, relative to the amount of P exported from the field with harvesting a typical crop of soybean, leading to a negative soil P balance (P applied – P removed).

In our study, only five of 28 site-years had plant stand reductions caused by fertilizer toxicity, when the fertilizer was placed in the seedrow. Rates of 22.5, 45 and 90 kg seed-placed P_2O_5 ha^{-1} reduced plant stands in one, two and five of those five site-years, respectively.

The second objective of the first study (Chapter 2) was to evaluate the soybean response to fertilizer rate and placement. Most of the research previously conducted in Canada and in the U.S., has reported inconsistent and infrequent yield increases to added fertilizer P. Moreover, the lack of P fertilization of soybean and the high P removal could lead to soil P declines, as well. In our study, only one site-year had a seed yield increase to added fertilizer P. Seed yield was significantly reduced in only two site-years, and only where fertilizer toxicity drastically reduced plant stand below 247,000 plants ha^{-1}. The low frequency of reduction in seed yield relative to plant stand was probably because of the compensatory growth of the soybean plants, which can increase the number of branches and pods when plant stand is suboptimal. The replant threshold for soybean is 247,000 plants ha^{-1}, at which seed yield will be below or equal to 95% of the yield obtained with an ideal plant stand.

The lack of response to added fertilizer P and the large P removals with crop harvesting indicates that soybean would prefer to feed on soil P reserves, instead of fertilizer P. Therefore, the main objective of the second study (Chapter 3) was to evaluate the soybean response to different background levels of soil P. However, there was no seed yield increase response to soil test P at any of our sites. This indicates that when producers in Manitoba claim that soybean has greater yields in soils with high soil test P, the high yields may be due to other factors, such as the overall soil fertility, history of manure application or better soil moisture.

Phosphorus concentrations in biomass and seed for the first study were frequently increased by P fertilization at sites with low soil test P. However, this extra P concentration was not converted to seed yield or quality, indicating that even though the plants absorbed some of the P applied with the fertilizer, these plants were not P deficient. Therefore, these responses had no nutritional benefit and seem to be luxury uptake.

Protein and oil were not affected by P fertilization, which has little practical importance, since soybean growers are not currently compensated for seed protein and oil concentration in the seed.

Soybean yield did not respond to P fertilizer even in soil with P levels as low as 3 mg kg^{-1} Olsen extractable P, which indicates that soybean is taking up phosphorus from soil reservoirs that are not accessed by the routine soil P test. In addition, there was no effect of soil test P on yield of soybean grown at sites with varying levels of soil test P.

4.2. Recommendations to Soybean Growers

Even though there was no positive response to P placement for the soybean crop, proper placement is important for increasing long term fertilizer efficiency and reducing environmental losses. Side-band placement would be recommended because the fertilizer is placed in close proximity to the seed, but not in direct contact with it, minimizing the risk of seedling injury. Also, side-banding places the fertilizer in a band below the soil surface, reducing P retention by the soil, and reducing losses of particulate and dissolved P in surface water runoff, a typical problem for broadcast applications.

Events of seedling damage in our study were rare, suggesting that Manitoba’s guidelines for seed-placed fertilizer are very conservative for soybean. However, a new maximum safe rate value of seed-placed fertilizer cannot be suggested from this study because there are many factors besides fertilizer rate that can increase fertilizer toxicity.

These factors include soil disturbance caused by seeding equipment, row spacing width, and soil moisture and texture. In our study, plant stand reductions were probably caused by the coarse-textured soils, low soil disturbance caused by some of the seeding equipment, high fertilizer rates and low soil moisture. However, the three years of field trials for this study generally had adequate precipitation and good soil moisture during the spring. Therefore, our study probably underestimated the risk of stand reductions for dry conditions.

With the results obtained in this project we could recommend that producers not fertilize their soybean crop because there is little chance of reward for doing that in the short term. However, the depletion of soil P caused by soybean uptake without P replenishment may be detrimental to yields of other crops in the rotation, which in the long term can affect productivity and sustainability of the cropping system.

It is important for farmers to consider a P “balance” or “budget”, in order to maintain soil P levels in the medium range of sufficiency, without declining into the low soil P levels since building up soil P fertility may require large rates of P and may not be economically viable in the short term with application of commercial fertilizer. However, if soil P is excessively high, soybean may be an excellent crop for depleting the soil P reserves in order to reduce the risk of environmental loss.

Soybean’s lack of response to P fertilization gives flexibility to when P fertilizer should be applied in the crop rotation. It does not matter if the P removed by soybean is replaced with an application of P to the soybean phase in the crop rotation or to another crop; however, at some point it is important to replace P removal in order to maintain soil P levels.

Some strategies for P fertilizer application in order to replace P removal by soybean will be described below, and can be directly applied to the soybean crop, or indirectly, applied to other crop in rotation, which is called rotational fertilization. Seed-placed P application can be maximized for the cereal crops in the rotation since these have high tolerance to salt toxicity and usually P removal by these cereals with grain and/or straw harvesting is less than the maximum safe rate of seed-placed P (56 kg P_2O_5 ha^{-1}), resulting in a net surplus of P for that year. However, special attention should be paid to the modern, high yielding, varieties of wheat, which can use up the equivalent of the maximum seed-placed P, resulting in no surplus of P.

Another option for indirect fertilizing for soybean is to apply P fertilizer during normal operations, to band or incorporate the fertilizer. Some producers in Manitoba are adapting their tillage equipment to pull an air-tank fertilizer cart. With a cheap investment, a set of hoses can be installed in the tillage tool to band P into the soil.

Periodic application of P may be another option, with one large application of P every three or four years of a high rate of P in order to balance removal and increase P fertility, in combination with annual rates of starter P, can be beneficial for plant uptake, maintain soil P levels, reduce risk of fertilizer toxicity and reduce environmental P loss, if properly applied. For example, canola has low tolerance to seed applied fertilizer, as well, and may require sulphur and P banding prior to seeding, perhaps in the fall. Phosphorus for soybean can be applied during this operation, which may be better used for the canola uptake and still replenish P removals. Also, the typical sources of P fertilizer in Canada are monoammonium phosphate (11-52-0) and ammonium polyphosphate (10-34-0). Therefore, it is important to consider the nitrogen benefit that is captured when these P fertilizers are applied ahead of crops such as wheat, canola and corn, which have high N requirement. When this bonus is accounted for in the N fertilizer purchase, there can be a benefit of about $10.00 per ha for applying these P fertilizers to these crops, compared to applying ammonium P directly to the soybean.

Building up soil P levels can take a long time and require large rates of P, which is costly if using synthetic fertilizer P. Manure and biosolids can be an alternative because applying manure based on the crop's nitrogen requirement can yield a surplus of P, which is sufficient to supply crop removal for many years. This surplus occurs because the ratio of N and P for crop requirement and removal, respectively, is much greater than in the manure. Therefore, when manure rate is based on the plant N requirement, there is a surplus of P for that particular crop. Nevertheless, strategies of P fertilization vary from farm to farm and there is no universal recipe. However, the P budget should be used in order to properly manage P fertilization.

4.3. Study Limitations

The studies presented in this thesis had some limitations which deserve to be mentioned and improved for future studies. The first limitation was the small area sampled for plant counts and mid-season biomass, which resulted in high coefficients of variation, reducing the power of detecting statistical differences for these early and midseason measurements, even though this strategy maximized the undisturbed area of the plots for measuring seed yield. Second, only one soybean cultivar was utilized in these studies, which was the cultivar with the largest market share in 2013. Other modern cultivars with higher yield potential may have greater P uptake, and be more likely to respond to P fertilization. Moreover, responsiveness to P can be a genetic feature, varying among cultivars. Another limitation would be the use of monoammonium phosphate (MAP) as the only source of P, even though MAP is the most common source of P in Canada. Liquid fertilizers, such as ammonium polyphosphate, could have different effects on seedling reduction caused by salt toxicity.

4.4. Recommendations for Future Research

Future research should include the investigation of other cultivars' response to added P, and the testing of different sources of P. Also, research about the best crop sequence in the crop rotation is ongoing in Manitoba but does not evaluate the rotational fertilization concept. Therefore, this could be further investigated.

Further investigations are required to evaluate the soil P pools that are being explored by soybean and the mechanisms that plants use to make P available, such as rhizosphere acidification. During the summer of 2014 and 2015, root samples of canola, wheat and soybean was collected in order to investigate a possible soil acidification at the rhizosphere of soybean roots which would solubilize Ca-phosphates, the main form of soil P reserves in Manitoban soils. For the first year, there was a trend in pH decline along the soybean growth cycle but results were not similar for the second year of study. The soil from the rhizosphere was obtained by gently hand separating the loose soil from the soil close to the root. However, rhizosphere soil is known to be at most three millimetres away from the root surface. Therefore, depending on soil moisture and texture, sampling rhizosphere soil by hand separation can be a challenge. Therefore, more rigorous studies on rhizosphere pH changes are justified.

4.5. Complementary Aspects of the Field Studies

Similar to other studies, we had expected that soybean would not respond to P fertilization but would respond to soil P fertility. In the fertilization study reported in Chapter 2, only one of six sites with Olsen P concentrations of 5 mg kg^{-1} or less responded to addition of P fertilizer. The high demand for P and rare response to P fertilization indicates a preference for soil P, and therefore, soybean could respond to soil test P concentration. However, in Chapter 3, there was no seed yield response to increasing concentrations of soil test P. Together, these two studies indicate not only that soybean is extraordinarily efficient in utilizing soil P, but also that the pools of P used by soybean may be not extracted with the standard agronomic soil test for P (e.g., Olsen P).

4.6. Preferential Uptake of Soil P Over Fertilizer P by Soybean

The lack of response to P fertilizer can be associated with the preferential absorption of P from soil rather than P fertilizer. Soybean has many mechanisms that facilitate P absorption from soil P reservoirs, such as rhizosphere acidification, release of phosphatases and organic acids, and mycorrhizal symbiosis.

In Manitoba, soils are generally characterized by high pH, in which Ca-phosphates and Mg-phosphates are abundant. When the soybean plants release protons in the root zone, causing rhizosphere acidification, these phosphates are dissolved, which become available for plant uptake. Rhizosphere acidification is common in legumes because of the greater absorption of NH_4^+, obtained with the biological nitrogen fixation, and also because of the greater uptake of cations by legumes, compared to other crops, such as cereals. More information on this topic can be found in the Appendix A.

In summary, the 35 site-years studied in these two projects gave us solid knowledge about the proper phosphorus fertilization practices for soybean production in Manitoba. The knowledgeable use of P is important for sustainable land management, supporting the continuously increasing crop productivity, improving fertilizer use efficiency and minimizing environmental losses.

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6. APPENDICES

Appendix A

A. Literature Review

A.1. Introduction

Canada has an important role in the soybean market worldwide. In 2012 Canada occupied the 6th place in the rank of soybean producer countries with an annual production of 5,086,400 MT (Food and Agriculture Organization 2016). In 2015, soybean seeded areas reached 560,729 hectares in Manitoba, which means a 5.4 fold increase in areas compared to 2007. During the same period, cereal crops such as winter wheat, oats and barley reduced seeded areas by 50, 54 and 61%, respectively (Statistics Canada 2016). This expansion of soybean areas in southern Canada was possible due to genetic improvement and introduction of cultivars with a small heat unit requirement and short growing season. In 2015, soybean provincial average yield was approximately 2576 kg ha^{-1} (Manitoba Agricultural Services Corporation 2016).

Following the increase in soybean acreage, there has been an increase in agricultural areas with soil P levels declining into the low levels of P. IPNI (2016) reported that 64% of the soil samples analysed for P in Manitoba tested below the critical soil P levels, which is 7% higher than the value of 54% estimated in 2010 (Fixen et al. 2010). One of the factors that make soybean an attractive crop in Manitoba is the low cost with reduced fertilizer inputs, since soybean acquires large amounts of the nitrogen required through the biological nitrogen fixation, and P fertilizer is usually not applied. In addition to the factor that soybean is usually not fertilized with P, the soil P mining in areas where soybean is grown can be explained by a few other factors. The first one is the high P removal by soybean (around 6.2 kg of P per tonne of seed) when compared to cereal crops (Manitoba Agriculture, Food and Rural Development (MAFRD) 2007). Second, the increasingly high yields of current crops when compared to varieties grown in the past. Kovács and Casteel (2014) observed greater phosphorus uptake of modern cultivars and at least 86% yield increase when compared to cultivars from eight decades ago (1920's). Third, typical P fertilizer rates are often insufficient to replace P removal of current crops, despite fertilizer being applied. Last, fertilizer P is typically applied with the seed during the crop seeding, but the low tolerance to seed-placed fertilizer limits the rate of fertilizer applied, mainly to soybean and canola, which are sensitive to high rates of P fertilizer in the seedrow and therefore, restrict the rate of P applied.

A.2. Soil Phosphorus Dynamics and Role in the Plant

Phosphorus (P) is taken up by plants by diffusion, mainly as the orthophosphate form, $H_2PO_4^-$ or HPO_4^{2-}, which is an inorganic form. Therefore, any other form of P in the soil needs to be converted to the orthophosphate form in order to be absorbed (Pierzynski et al. 2005). In alkaline soils, HPO_4^{2-} is the predominant form while $H_2PO_4^-$ is more prevalent in low pH soils. Soil pH has an important role on P availability. Retention by Ca and Mg is likely to occur in alkaline soils, and retention by Fe and Al can be the most limiting factor in acidic soils (Pierzynski et al. 2005). Usually the amount of inorganic P available for plants uptake is very small if compared to the total inorganic and organic P present in soil. These stable, unavailable forms of P need to be dissolved, desorbed or mineralized in order to be transformed in plant absorbable forms. Therefore, roots have an important role for accessing P. Retarded root growth, low soil P and poor conditions for P diffusion can reduce the ability of plants to reach P in the soils, inducing the plant to P deficiency (Kovar and Claassen 2005).

Phosphate is used as a structural element, which makes the bridges between ribonucleosides units forming macromolecules. Since P is component of DNA and RNA, lack of P can directly affect protein content of seeds. For energy transfer, phosphate bonds are used to store the energy liberated during respiration, glycolysis and photosynthesis in order to form adenosine triphosphate (ATP). Inorganic phosphate also participates in many enzyme reactions as a substrate or an end product (Marschner 1986).

In legume seed, P is mostly found as phytate and usually composes approximately 50% of the total P in the seed, which is concentrated in the cotyledons and supplies the P required by the plant in early development stages (Marschner 1986). Phosphorus deficiency symptoms can be expressed by the purple or reddish color of the leaves, appearing on old leaves since P is a mobile nutrient. The reddish colour occurs because anthocyanin formation is enhanced. Plant size is reduced and plants often show a dark green color, as well, which is caused because cell and leaf expansion are more affected than the chlorophyll formation, resulting in a higher concentration of chlorophyll in plant tissue (Marschner 1986). However, in soybean, P deficiency symptoms are not always clear and P deficient plants can be vulnerable to water stress and reduce N uptake. Therefore, additional P supply to the plant can alleviate drought stress and also increase nitrogen uptake of P deficient plants (Jin et al. 2006).

Nevertheless, in order to prevent plant deficiency and maximize phosphorus use efficiency, reducing retention by the soil and potential environmental losses, phosphorus needs to be applied at right rate, right place, right timing and right source, which will be discussed further in this review.

A.3. Rate

A.3.1. Starter Phosphorus and Nitrogen

Many areas in North America have cold and wet soils after the snow melt during the spring and therefore, crops are usually seeded under these adverse soil conditions. These conditions are unfavorable to nutrient diffusion, especially for phosphorus and potassium, and may inhibit plant root growth, reducing nutrient uptake and root and shoot development. Crops such as cereals and canola, respond to the “pop up” or “starter” fertilizers, which are fertilizers applied at small rates with or close to the seeds at planting time, in order to supply the early crop demand (Sims and Kleinman 2005). Grant et al. (2001) reported that adequate supply of P is essential at early growth stages in order to reach yield potential because P limitation at this point could be carried out throughout the crop cycle, even when P supply is adequate later in the plant growth.

Studies on the effects of starter fertilizers for soybean have found infrequent yield increases to the early season application of fertilizer. The lack of soybean response to starter P may be because of the low influx of P by the plant in early stages, since the cotyledons can supply early P requirement, or because soybean is usually seeded into warm soils (at least 10^o C), when root growth and P diffusion are less inhibited (Lauzon and Miller 2008; Barber 1978). Barber (1978) observed low influx of soil P in early stages of soybean growth, which was assumed to be due to the large P supply from the cotyledons. However, a substantial P influx was observed at about 80 days after emergence, which coincides with the highest P uptake by the plant (Below et al. 2015).

Starter N fertilizer could be beneficial to early root and shoot growth since a period of at least 14 days is needed until the nodules start fixing N (Hardy et al. 1971). Osborne and Riedell (2006) found significant soybean yield response to starter N side banded at the rate of 16 kg N ha^{-1} as ammonium nitrate and urea in two of three years of study. This yield increase could be attributed to higher biomass accumulation at V3-V4 and R1, and to the higher plant N concentration. Conversely, Hankinson et al.

(2014) found no yield increase to urea applied as starter fertilizer at 34 kg N ha^{-1} but nodulation was reduced at R1 growth stage because of the N fertilizer supplied. However, in this same study, triple superphosphate (0-45-0) or diammonium phosphate(18-46-0) were applied at 45 kg P_2O_5 ha^{-1} applied in side band without urea and resulted in significant seed yield increases of 243 and 239 kg ha^{-1}, respectively. Even though fertilizer applied with the seeds in small rates usually is beneficial to the crop, some crops may be sensitive to the fertilizer toxicity and therefore, have seedling emergence reduction. Rehm and Lamb (2010) observed that starter fertilizer applied to soybean did not increase or decrease seed yield. However, plant emergence was significantly reduced by the seed-placed fertilizer. Similar effect of fertilizer on plant stand reduction was observed by Clapp and Small (1970) but seed yield was also reduced as consequence of the severe plant stand reduction.

In soils with low P fertility in Manitoba, the yield of typical crops grown usually increases in response to P fertilization. For instance, Karamanos et al. (2010) observed hard red spring wheat yield increases to P fertilization in 100% of the sites where soil P levels were below 5 mg kg^{-1} Olsen extractable P. However, soybean yield increase to P fertilization in North America has been inconsistent and infrequent, even in areas where soil P levels are below the critical concentration levels (Gervais 2009; Slaton et al. 2010; Borges and Mallarino 2000, Lauzon and Miller 2008; Florence 2015; Blackmer et al. 1992; Mallarino and Haq 2005). Previous research in Manitoba did not find yield increase to rates up to 75 kg ha^{-1} (Gervais 2009). However, Bullen et al. (1983) observed soybean yield increases, depending on fertilizer placement and rate. In

Ontario, soybean early season biomass and seed yield did not increase in response to seed-placed fertilizer (Lauzon and Miller 2008).

A.4. Placement of P

Efficiency of fertilizer P use by crops in the first year of application is usually very low because of the rapid conversion of the soluble form of the P applied with the fertilizer into less soluble forms. In low pH soils, soluble P is rapidly converted to Fe and Al phosphates and in high pH soils, soluble P is converted to less soluble forms of Ca and Mg phosphates (Hedley and McLaughlin 2005). These phosphates formed have lower solubility than the fertilizer applied, which results in low efficiency of the P in the year of application. Therefore, proper fertilizer placement is fundamental to improve crop uptake of the nutrient in the fertilizer and also to minimize P retention by the soil (Bundy et al. 2005). Placement is also an important tool for managing risk of P losses through surface water runoff, which can carry out dissolved and particulate P into water bodies, resulting in eutrophication due to the increased algae growth stimulated by high concentration of P in the water. Smith et al. (2016) observed that 16 to 19% of the granular fertilizer applied as broadcast on the soil surface was lost in only one rainstorm event, and that 98% of the soil P losses with the water runoff could be reduced by placing the fertilizer one cm below the soil surface. This study demonstrates the potential losses of broadcasting fertilizer P on the soil surface.

A.4.1. Seed Placed P

A.4.1.1. Fertilizer Toxicity. Fertilizer P application with the seed is a common practice for crop production in Manitoba, not only at a starter rate but also for the full crop requirement. With the transition of crops in Manitoba, switching from cereals to soybean, the seeding equipment for solid-seeded crops was kept, which often does not allow fertilizer to be placed separate from the seed, through a side-band or mid-row fertilizer placement. Furthermore, most of the current seeding equipment has low seed bed utilization [(row opener width / row spacing)*100], resulting in high concentrations of fertilizer placed with the seeds, which can potentially cause damage to seeds and seedlings.

Fertilizer salt content can cause seedling toxicity by increasing the soil solution's salt concentration to be greater than plant cell's concentration, resulting in high osmotic pressure in the soil, which does not permit proper water supply to the seedling during emergence and development. The fertilizer salt index was created in order to compare the salt content of different fertilizers, being calculated by the ratio of increase in the fertilizer osmotic pressure to the $NaNO_3$ osmotic pressure (Rader et al. 1943). This index helps to identify the products with low potential risk of toxicity but cannot be used as the only guidance for fertilizer rates since seedling toxicity can be reduced due to other factors and plant's tolerance to salts varies among species (Laboski 2008).

Phosphorus fertilizers containing ammonium-N, such as ammonium phosphate (MAP), diammonium phosphate (DAP) and ammonium polyphosphate (APP), can also be toxic to plants when the ammonium form of nitrogen is transformed to ammonia. The toxicity caused by ammonia is enhanced in fertilizer sources that have high pH in the saturated solution zone, which favours the transition of nitrogen from the ammonium form to ammonia (Hedley and McLaughlin 2005). For instance, DAP has a high nitrogen concentration and high pH (8.0) in the reaction zone, containing greater ammonia toxicity than MAP, which has low nitrogen content and low pH (3.5) in the reaction zone, despite the greater salt index per unit of P for MAP than DAP (Rader el at. 1943). However, overall, MAP can be more toxic to plant emergence than DAP and APP because of its high salt index per unit of nutrient (Gelderman 2007).

Many other factors can influence fertilizer toxicity to seedling emergence, such as soil moisture, soil texture, row spacing, soil disturbance, fertilizer rate and crop susceptibility to fertilizer toxicity. The Manitoba Soil Fertility Guide recommends the maximum of 11 kg of P_2O_5 ha^{-1} placed with soybean seed and only at row spacing below 38 cm. For more tolerant crops such as cereals, the maximum safe rate of fertilizer placed with the seeds is 56 of P_2O_5 ha^{-1}, five times greater than the safe rate for soybean (MAFRD 2007). As the row spacing widens or the spreading of seed and fertilizer is narrowed, resulting in low seed bed utilization, the fertilizer concentration increases in the seed row and therefore, can be more toxic to the plants. For instance, 20 kg of fertilizer placed with the seed at 20 cm row spacings has the concentration doubled when the same 20 kg of fertilizer is applied at 40 cm row spacings. In addition, dry soil conditions may increase fertilizer toxicity because of greater osmotic pressure in the soil zone close to the fertilizer. Conversely, as the soil water content increases, the fertilizer salts are diluted and the osmotic pressure is reduced. Dubetz et al. (1959) observed less crop emergence as the soil moisture was decreased in fertilized treatments when compared to the control treatment. Fine-textured soils have greater water holding capacity and usually have more plant available moisture than coarse-textured soils (Gelderman 2007). Rader et al. (1943) reported that the change in osmotic pressure caused by the addition of fertilizer was more intense in medium to coarse-textured soils than in clays soils. In summary, any factor related to the fertilizer applied with the seeds that reduce the water supply to the seed, can increase toxicity and reduce crop establishment.

Cereal crops can usually tolerate high rates of seed-placed fertilizer, unlike oilseeds, such as soybean, canola and flax, which are susceptible to plant stand reduction. Gelderman (2007) ranked the crops tolerance to seed-placed fertilizer from the most to the least tolerant as: corn > sorghum > oats > sunflower > wheat > barley > soybean > flax. In addition to the reduced plant emergence, plants can also have slow emergence caused by the fertilizer toxicity. Grenkow (2013) found that 40 kg of P_2O_5 ha^{-1} applied as MAP with canola seed resulted in plant stand reduction as well as a two week delay in the plants reaching 90% establishment of their final plant stand. Bullen et al. (1983) also observed soybean biomass yield reduction at full pod growth stage (R4) followed by seed yield reduction when 58 kg P_2O_5 ha^{-1} was applied seed-placed at two locations in Manitoba. Rehm and Lamb (2010) found that high rates of liquid fertilizer placed with or near to the soybean seed caused stand reduction. On the other hand, Gervais (2009) did not observe plant stand decrease to fertilizer seed-placed in five sites established over three years in Manitoba, even when 75 kg P_2O_5 ha^{-1} was applied as MAP in furrow. Lauzon and Miller (1997) also did not observe plant stand reduction or seed yield increase when the rates of 39 and 8.7 kg P ha^{-1} were seed-placed as a liquid fertilizer (10-15.8-0).

A.4.2. Broadcast P

Broadcasting fertilizer is a practical way of applying phosphorus fertilizer, on the soil surface, followed or not by a tillage incorporation of the fertilizer, allowing application of high rates in a low time consuming operation. However, broadcast applications of phosphorus are very inefficient, as the fertilizer can be stranded above the active root zone and contact between soil and fertilizer is increased, reducing fertilizer efficiency caused by P retention by the soil (Tisdale et al.1993). Furthermore, phosphorus applied on the soil surface can be lost through surface water movement, as particulate P when soil particles are carried by soil erosion, or as dissolved P with the soluble fraction of P in the fertilizer or manure (Sims and Kleinman 2005). On the other hand, when the fertilizer is mixed to a larger volume of soil, a greater number of roots can contact the fertilizer (Randall and Hoeft 1988). Response to the fertilizer placement may be affected by the soil P status and by the soil moisture conditions, as well. Ham et al. (1973) observed that with low soil moisture and low soil test P, the greatest yield was obtained with the broadcast fertilizer, when compared to seed-placed, side-band or the combinations of two or more placements. This fact can be explained by the lower uptake of P from the fertilizer band in dry conditions, relative to the broadcast fertilizer that could be present in dry and moist soil layers.

A.4.3. Banded P

Banding the fertilizer, in mid-row or side band, is an efficient way of placing the fertilizer in the soil because P is more efficiently accessed by plant root, and is also less strongly retained by the soil due to the smaller surface area of contact between fertilizer and soil (Grant et al. 2001). Even though the fertilizer banded in the soil has limited root access for occupying a small zone in the soil, plant can benefit from that if some roots grow in the fertilizer band, which may have greater nutrient availability for being less retained by the soil (Randall and Hoeft 1988). Strong and Soper (1974) observed that some crops have greater ability of growing roots within the reaction zone of the fertilizer band, which is beneficial for P uptake. Borges and Mallarino (2000) did not observe soybean yield or early growth consistent response to fertilizer P placement. However, P uptake was increased by banding the fertilizer, as deep-band or side-band, when compared to the broadcast application.

A.5. Timing of P Fertilization

For Manitoba conditions, where soybean yield response to P fertilizer has rarely been measured, it is hard to predict whether fall or spring fertilizer application will be the best short term management strategy for fertilization. Timing decisions depend on many factors such as fall labour and equipment availability, time available after harvesting and before ground freezing, fertilizer prices and crop management practices, such as post-harvest and pre-plant tillage. Moreover, previous studies on timing for P fertilization found that timing is not important for increasing seed yield (Mallarino 2009, Slaton 2009, Slaton 2010).

Two years of studies in Arkansas comparing two different rates of P in combination with fall (December) versus spring (February) application on soybean showed an increased recovery from the spring-applied fertilizer, resulting in higher soil test P (STP). However, despite the increase in STP, there was no increase in soybean seed yield (Slaton et al. 2009, Slaton et al. 2010). Mallarino et al. (2009) evaluated the interaction of P rates and timing (spring versus fall) for P broadcast application on soybean and found seven cases of yield response to P in a total of 20 trials, when Olsen P test was below 13 mg kg^{-1}. However, there was no seed yield or early stage biomass response to the timing of application. Randall (2012) reported that a triennial application of P was equivalent to the annually applied P once every three years in order to reach satisfactory yields.

In theory, the best timing would be spring application once the fertilizer is exposed to the soil activity for a shorter period, which implies higher efficiency than fall application (Pierzynski et al. 2005). The longer the contact between fertilizer and soil, the greater and stronger is the P retention. Also, fall broadcast application increases the risk of runoff losses of P during spring snow melt, causing eutrophication in surface water bodies, which is especially likely to occur in the Manitoba landscape (Li et al. 2011; Smith et al. 2016). It is estimated that agricultural activity in Manitoba contributes to 15% of the total P loaded into the Lake Winnipeg (Lake Winnipeg Stewardship Board 2006).

A.6. Sources of P

Studies comparing different sources of synthetic phosphorus fertilizer for soybean are scarce. Bureau et al. (1952) studied different sources of P, which are not the major phosphorus fertilizer sources currently, and found no response to P source or rate. In Canada, the most typical source of P fertilizer is monoammonium phosphate (MAP 11-52-00) (Statistics Canada 2016). In alkaline soils and/or with high content of

Ca, ammonium phosphate fertilizers such as monoammonium phosphate and ammonium polyphosphate tend to have better efficiency than the other forms of phosphates because of the low pH in the fertilizer reaction zone, and for not being a Ca-phosphate fertilizer. The high pH and high content of Ca in the soil can transform the soluble P in more stable forms of Ca-phosphate in the soil (Hedley and McLaughlin 2005). Diammonium phosphate (DAP 18-46-0) although has greater nitrogen content than MAP, the high pH in the reaction zone tend to increase ammonia losses and also favours P retention by Ca and Mg in the soil (Hedley and McLaughlin 2005).

Liquid forms of P can be beneficial for diffusing slightly further than granular fertilizer (Lombi et al. 2004), and also can reduce the risk of fertilizer toxicity for being diluted in water and presenting low salt index. Salt index is another important factor to be considered when the fertilizer is intended to be applied with the seeds. Hoeft et al. (1975) observed that MAP was more detrimental when placed with soybean seed than DAP. Even though DAP can cause greater ammonia toxicity due to the high N content and high pH in the reaction zone, MAP has greater salt index for unit of nutrient (Rader et al. 1943).

Another benefit of the use of ammonium phosphate forms is the presence of the ammonium cation, which stimulates the absorption of the orthophosphate when taken up by the plants (Flaten 1989) and also improve rhizosphere acidification through the release of protons (Riley and Barber 1971), which will be discussed later.

Other sources of P such as manure and biosolids are beneficial to soybean and can be as efficient as the synthetic fertilizer. Slaton et al. (2013) observed that poultry manure was as efficient as synthetic fertilizer to supply P to soybean plants. Because of the high rates of byproducts applied, the quantity of phosphorus supplied is enough to replenish P removal by the crops for several years (Ajiboye et al. 2007), which is a strategic fertilization tool for fertilizing crops that do not likely respond to annual application of P fertilizer.

A.7. Soil P fertility

In addition to the short term P management decisions about if and how to apply fertilizer during the fall or spring, there is also the long term P management strategy to consider, in which soil fertility levels are enhanced, maintained or depleted over several years. Soybean seems to respond more to soil test P (STP) than to P fertilizer (Randall et al. 1997). There are two basic ways to increase STP. The first one would be P fertilization focusing on building up soil P levels when applying P; some extra P is added above the rate of crop removal and after every crop some surplus P will be left over. One option for accomplishing this is applying manure or biosolids based on the nitrogen supply to the crop. Concentrations of available N and total P in manure are usually similar; however, P removal at harvest is about half of the crop’s N requirement, resulting in extra application of P, which contributes to increased reserves of soil P. Slaton et al. (2013) observed that poultry litter manure was as efficient as synthetic fertilizer to supply P and K needs for high yielding soybean. In a long term trial conducted by the National Centre for Livestock and the Environment, the P balance after manure applications over 6 years period based on the crop N requirement was 1105, 485 and 137 kg P ha^{-1} for solid pig, solid dairy and liquid pig manure applications, respectively. From these P surpluses, 65%, 23% and 14% was converted to Olsen P soil test increase, respectively, showing the contribution of manure application to the long term P management (Fraser and Flaten 2014).

Some recommendations aim to increase soil P fertility levels instead of supplying P fertilizer straight to the crop. As long as soil P is maintained at high levels of sufficiency, there is reduced chance of crop yield increase to fertilizer P (Randall et al. 1997). In two long term trials in Minnesota, conducted by Randall et al. (1997) over 20 years on soybean and corn rotation, treatments with 56 and 112 kg P_2O_5 ha^{-1} were applied every year and a treatment with 150 kg P_2O_5 ha^{-1} was triennially applied. Randall et al. (1997) observed similar yield response to P annually applied as 50 kg P_2O_5 ha^{-1}, or to the rate of 150 kg P_2O_5 ha^{-1} triennially applied. This strategy may be especially suited to soybean. Kalra and Soper (1968) observed that soybean has an exceptionally large capacity to utilize soil P instead of fertilizer P, which meant that 76% of the soybean's P uptake was supplied by the soil P reserves.

A.8. Rotational Fertilization

Several studies have demonstrated infrequent soybean seed yield responses to P fertilization. The lack of P response in addition to the need for field operation maximization has led some producers to opt for rotational P fertilization, which is the preferential application of P fertilizer to a more P responsive crop in the rotation or whenever is more convenient in the cropping system. In the crop rotation, P fertilizer is applied to a responsive crop and the unresponsive crop does not receive P fertilizer, or only a small rate applied as a starter P. For example, a common practice in northern US production areas is the application of P to the corn crop and no fertilization on soybean crop in the subsequent year. In a study conducted in South Dakota in 1992, ammonium polyphosphate was banded at 0, 12, 24 and 49 kg P ha^{-1} within the corn crop prior to soybean in the crop rotation. Soybean seed yield increased in response to the residual P from the fertilizer applied to the preceding corn year in the rotation (Bly and Woodard 1997).

A combination of soil P fertility and P fertilization can be a successful fertilization strategy for crop production. For example, a high rate of P fertilizer can be periodically applied to build up soil P, and a lower rate is applied annually in order to maintain soil P levels, or supply early crop requirements, as a starter fertilizer. In a Saskatchewan study, wheat yield was maximized by an initial broadcast application of 80 kg P ha^{-1}, which increased the soil P level, plus an annual rate of 20 kg P ha^{-1} applied as seed-placed, although there was significant, but smaller, yield increase by the single applications of broadcast P or seed-placed P annually applied (Wagar et al. 1985). Similarly, Ham et al. (1973) found greater yields of soybean produced in low soil P fertility and drier soil conditions, when a combination of broadcast and seed-placed fertilizer (N-P-K) was applied to the crop, even though the single application of broadcast or starter (seed-placed) fertilizer increased seed yield, as well, but to a smaller degree than the combination of placements.

When applying the fertilizer to the crop rotation, an important consideration is which crop should receive the fertilizer application. Grant et al. (2009) observed that P fertilization applied directly to the flax crop or indirectly, by applying P to the canola crop in the previous year, did not increase flax yield. However, early season concentrations of tissue P in flax were greater when P was applied to the preceding crop. Another important factor to be considered is the amount of nitrogen applied with the P fertilizer. The content of nitrogen in P fertilizer can be better used for crops that do not fix nitrogen biologically. Even though the rate of nitrogen applied in this case is low, it can be discounted from the nitrogen fertilizer budget for the non-legume crop and therefore, saving the nitrogen fertilizer cost for the crop that receives the P fertilizer in the rotation.

The phosphorus budget for agronomic purposes is a simple concept which accounts for the amount of P applied as fertilizer or manure and the amount of P removed with the portion of the crop that is harvested. After subtracting the P removal from the total P applied, ideally, there should be no surpluses or deficits unless soil test P is excessively low or high, respectively. If the soil P test is in the low range of sufficiency, a surplus can be beneficial to increase soil P levels (Bundy et al. 2005). However, there is no interest in P surpluses in soils with high soil test P because increases in soil test P can also result in greater P losses (Sharpley et al. 2001). Considering the P budget and soil P levels, producers can decide on fertilizer P rates and where in the rotation the fertilizer will be applied. For instance, in long term trials established in Iowa, plots with high soil test P were cropped with corn and soybean in rotation for 10 to 20 years, until responses to fertilizer P were observed, after soil test P was declined. Conversely, in order to maintain soil P levels, rates of 13 -17 kg P ha $^{-1}$, had to be annually applied (Mallarino and Dodd 2005).

Phosphorus applied in the rotation must supply the needs of the current crop and also ensure residual P to supply the requirement of a subsequent crop in the rotation, until P fertilizer is applied again. Randall et al. (2001) observed that applying the fertilizer for soybean prior to the corn crop in the rotation provides residual P that will be used by the soybean crop. However, the rate of P applied to the corn must be sufficient to balance P removal for both crops. Therefore, the assumption that side-band placement is two times more efficient than broadcast may encourage farmers to lower their rate of P application to corn and not allow enough residual P for soybean uptake.

Phosphorus fertilization can be classified in four basic strategies, depending on soil P level. The first strategy would be applying fertilizer based on the economical yield return, which generally does not allow the application of sufficient rates to replace crop P removal. Second, when soil levels are below a critical concentration level, fertilizer is applied in order to supply the crop removal, plus an extra amount in order to gradually build up soil P levels, up to the medium to high levels of sufficiency, where phosphorus fertility will not be a productivity limiting nutrient. Third, a fertilizer rate can be applied to the soil in order to replace crop P removal, based on the historic yields, and therefore, keep soil P levels at the medium level of sufficiency. Last, when soil P levels are high, chances of losses are high and crop may have its entire P requirement supplied by the soil P reserves. In this case, fertilizer is not necessarily applied, or a small rate can be applied as a starter fertilizer (Bundy et al. 2005).

A.9. Soybean Plant Stand Compensation

The threshold for reseeding soybean is determined when the plant population is not sufficient to produced 95% of the yield produced with an optimum plant stand. In Manitoba and in some other areas in North America, the replant threshold for soybean is 247,000 plants per hectare (Lee et al. 2008; Conley and Gaspar 2015; Mohr et al. 2014). Soybean plants have a great ability for compensatory growth and when the plant stand is suboptimal, more branches and pods are produced and therefore, seed yield is maintained (Carpenter and Board 1997).

Because of the compensatory growth, soybean plant is very versatile and fertilizer effects on plant stand and early biomass yield may not affect seed yield. Phosphorus fertilized soybean often produces greater biomass and P uptake than the unfertilized soybean; however, seed yield is often unaffected by the fertilization (Bly and Woodard 2008; Rehm and Lamb 2010). The opposite can also occur, when there is very little effect of P fertilization on mid-season biomass and there is significant differences in seed yield (Borges and Mallarino 2000).

A.10 Seed Quality

Protein and oil seem to have an inverse relationship; an increase in protein concentration decreases the oil concentration and vice versa. Ham et al. (1973) observed no increase in seed protein and/or oil concentrations to P fertilization, despite the increase in seed yield. Mallarino and Haq (2005) also observed that seed protein and oil concentration responded poorly to P fertilization. However, oil and protein tended to have an inverse relationship, as the increase in one would decrease the concentration of the other, and vice versa.

A.11 Tissue P Concentration

Phosphorus nutrition status of soybean plants can be assessed through plant tissue sampling and analyses for P. Recommendations are for sampling plant tissue at R1 growth stage by picking the most recent expanded trifoliate. The normal concentration range for P levels in soybean tissue at this stage is between 2.5 and 5.0 g kg^{-1} (MAFRD 2007). However, phosphorus concentration of soybean plants may be poor indicator of yield potential because phosphorus accumulation in soybean leaves is not necessarily remobilized to the seeds. Therefore, plants grown in P deficiency can have P concentrations that are similar to those for plants grown in high P fertility soils; also, luxury uptake of P by soybean does not convert to extra seed yield (Craft-Brandner 1992). Although there is poor net remobilization of leaf P into grain yield, Below et al. (2015) observed that modern cultivars of soybean remobilize about two thirds of the P in leaves and stems into seeds, during the reproductive stages of the plant, resulting in a P harvest index of 81%, which means that 81% of the P taken up by the aerial part of the plants is harvested with the seeds. In this same study by Below et al. (2015), the maximum P accumulation occurred at R6.5 growth stage (49.9 kg P ha^{-1}), and the highest P accumulation rate occurred in R4 growth stage (0.34 kg P ha^{-1} day^{-1}).

A.12. Possible Explanations for Soil P Acquisition and Lack of Response to P Fertilizer

Under stress from nutrient deficiency, plants find many ways to overcome the lack of nutrients. The most common ways to access nutrient reserves would be through root elongation, multiplication or root growth on soil layers where there is more nutrient available and increase in quantity of root hairs (Watt and Evans 2003; Foehse and Jungk 1983). Watt and Evans (2003) studied the root system of soybean and white lupin (*Lupinus albus*) under P stress and observed that soybean increased the root length and soil exploration, while lupin increased the number of cluster roots, which are very efficient for P uptake.

The second mechanism by which plants can improve nutrient availability including P, is through the arbuscular mycorrhiza endosymbiosis. This is a type of fungal-plant association where part of the fungal hyphae develops inside the root and is responsible for supplying nutrients to the plant such as P. On the other hand, the plant is responsible for supplying carbohydrates to the fungus (Vanderleyden et al. 2010). Mycorrhizal associations take up P from the soil and synthesize polyphosphates; these are transferred to the host roots and are well accepted because plants also synthesize polyphosphates in order to store energy (Marschner 1986).

In addition to the physical changes in the plant, such as extra root growth, there is chemical modification and microbial association that can make soil nutrients more available. Some plants can promote rhizosphere acidification through the release of protons, which in high pH soils can release P bound to calcium and magnesium.

Another approach used to enhance P uptake under P deficiency is the release of organic acids and enzymes into the rhizosphere. Legumes tend to release citrate and malate more than other crops. The organic acids are responsible for solubilising inorganic P that is otherwise not readily available and for mineralizing organic P fractions (Li 2011; Strom et al. 2005; Gerke 2015; Shi et al. 2015; Jones 1998). In addition, plants can release phosphatases, such as phytase, which hydrolyze inositol phosphates, phosphoglycerates and nucleic acids (Li et al. 1997; Condron et al. 2005).

A.12.1 Effects of Biological Nitrogen Fixation on Phosphorus Availability

The biological nitrogen fixation process, itself, does not acidify the soil in the plant rhizosphere. However, during the NH_4^+ assimilation, there is extrusion of protons, which are responsible for rhizosphere acidification in legumes and in plants supplied with ammonium fertilizers. In legumes, ammonium is the first compound originating from N_2 fixation. When ammonium enters in the cytosol, there is depolarization of the plasmamembrane potential. Also, ammonium is dissociated to ammonia and H^+ prior to being incorporated into glutamate. These reactions will stimulate a proton release by ATPase, resulting on H^+ efflux in the rhizosphere (Schubert 1995).

Because nitrogen is taken up in large amounts by the plant, depending on the source of nitrogen taken up, the plant can excrete more protons or hydroxides. In low pH, nitrate fed plants can release hydroxides and therefore, alkalinize the rhizosphere, improving availability of P (Hinsinger 1999; Gahoonia et al. 1992; Hinsinger and Gilkes 1996). Plants fed on ammonium-nitrogen tend to excrete protons in order to maintain the internal ionic balance, and plants fed with nitrate tend to excrete hydroxides (Riley and Barber 1971). In a study by Tang et al. (1999), legume plants were fed with nitrate and supposedly would release anions into the rhizosphere. However, in this study, plants excreted cations, proving the potential of legumes to promote rhizosphere acidification.

Legumes are expected to absorb more cations than anions during the nitrogen fixation process resulting in higher efflux of positively charged compounds (Hinsinger et al. 2003). Zhou et al. (2009) compared the rhizosphere acidification and the protons efflux caused by faba bean (*Vicia faba*), soybean and corn (*Zea mays*) and observed large amounts of acidification of the nutrient solution in the initial 22 days of growth and a 14 fold increase in the protons released for faba beans under P deficiency compared to soybean or corn. Raven et al. (1990), summarized the net H^+ release for several legumes as mol of H^+ release per mol of N assimilated. Estimated values go from 0.24 to 1.55 mol H^+ per mol N fixed. Soybean can excrete about 1.02 mol of H^+ per each mol of N_2 symbiotically fixed (Raven et al. 1990). Marschner and Romheld (1983) observed that legumes fixing nitrogen could reduce the rhizosphere pH from 6.0 to values as low as 4.5, which was measured as well in the rhizosphere of corn plants when supplied with ammonium nitrogen.

The rhizosphere acidification caused by the protons release solubilises some phosphate compounds in high pH soils. For instance, in places where phosphorus is precipitated as calcium compounds, this localized acidification has an important role on the supply of P to the plants (Raven et al. 1990). Rhizosphere acidification can promote the solubilisation of P pools that are not extracted by the conventional agronomic soil tests for P (Gahoonia and Nielsen 1992; Hinsinger 1999). Also, proton excretion helps to prevent or at least to alleviate iron chlorosis symptoms in high pH soils (Wallace 1982) and in acidic soils (Romheld 1987).

In summary, the inconsistence of soybean response to P fertilizer in low soil test P and high pH soil could be due to the soybean's ability to acidify the rhizosphere and solubilize calcium phosphates, which are naturally abundant in some Manitoba soils.

A.13. Conclusion

Soybean is very robust plant in terms of phosphorus nutrition. Response to phosphorus fertilization in North America is inconsistent and infrequent. However, soil phosphorus fertility maintenance is desired because there is substantial removal of P with harvesting, which in conjunction with the low response to P fertilization, indicates that soil P reserves are preferentially explored. Moreover, other crops in the rotation are likely to benefit from maintaining soil P fertility.

Fertilizer toxicity from seedrow placement is a concern and can drastically reduce plant emergence. Factors such as fertilizer rate, soil moisture, precipitation, soil texture, and seed bed utilization should be considered when deciding about seed-placing the fertilizer. Proper placement is desired not only for reducing the risk of fertilizer toxicity but also to increase the fertilizer use efficiency and reduce phosphorus losses by water runoff and soil erosion.

Due to the risk of fertilizer toxicity and the lack of response to P fertilization, rotational fertilization for P is recommended and therefore, P should be applied to a crop that is more responsive or less sensitive to fertilizer injury. A phosphorus budget should also be considered in order to avoid soil P declines and avoid over application of P, which can be an environmental concern.

Appendix B

B. General Information (Chapter 2)

Table B.1 Monthly precipitation at the sites established in 2013, 2014 and 2015.

Site		Precipitation (mm)[z]				
		May	June	July	August	September
2013	Melita	63.4	119.4	162	39.2	86.2
	Brandon	59.5	149.2	69.8	68.4	36.0
	Carberry	84.2	72.6	68.2	68.8	51.0
	Portage	91.7	79.2	95.9	66.2	36.3
	Carman	116.0	50.6	49.2	59.7	31.0
	Forrest	47.4	149	66.4	76.4	49.8
	St. Adolphe	87.3	60.8	90.3	75.4	33.1
	Beausejour	40.0	49.0	61.0	32.0	33.0
	Arborg	19.4	52.2	83.4	49.8	34.7
	Roblin	24.8	92.8	101.6	16.2	36.2
2014	Melita	104.8	152.5	40.6	102.3	23.2
	Brandon	107.9	251.6	25.6	70.4	47.2
	Carberry	71.4	136.9	24.8	105.3	43.9
	Portage	34.7	134.4	27.3	107.0	55.6
	Carman	30.9	116.7	47.5	122.4	46.6
	Forrest	114.6	170.8	37.0	69.0	48.4
	St Adolphe	66.8	157.1	40.3	91.8	24.8
	Beausejour	68.3	152.7	52.3	54.7	85.3
	Arborg	37.3	131.7	30.4	138.6	44.9
	Roblin	44.6	132.7	19.2	103.4	38.2
2015	Melita	69.0	111	15.0	53.2	59.6
	Brandon	48.6	37.4	64.8	59.5	39.2
	Carberry	54.5	55.1	126.7	94.8	30.7
	Portage	81.7	64.1	170.2	82.9	20.8
	Carman	98.8	75.3	109.3	47.3	42.0
	Forrest	39.2	57.9	73.3	75.4	23.8
	St Adolphe	100.3	83.2	129.0	69.8	69.1
	Beausejour	83.0	67.8	133.4	139.2	32.6
	Arborg	51.1	42.4	146.9	69.4	30.5
	Roblin	26.2	19.0	120.6	47.8	53.1

[z] Data retrieved from the Manitoba Agriculture and Rural Development website, on site weather station or a nearby weather station.

Table B.2 Manitoba soil survey information referent to the sites established in 2013, 2014 and 2015.

Site	Year	Soil Series	Soil Type[z]	Agricultural Capability[w]
Carman	2014	Denham	OBC	1
Carman	2015	Rignold	GBC	1
Roseisle	2014	Almasippi	GRBC	3M
Roseisle	2015	Long Plain	GR	4M
Arborg	2013	Fyala	PRHG	$3W^{4}5W^{3}6W^{3}$
Arborg	2014	Fyala	PRHG	$3W^{4}5W^{3}6W^{3}$
Arborg	2015	Tarno + Fyala	RHG + PRHG	$3W^{5}3W^{5}$
Beausejour	2013	Dencross + Osborne	OBC + RHG	$2W^{5}3W^{5}$
Beausejour	2014	Peguis + Marquette + Kline	GDGC + GRBC + RHG	$2W^{5}2W^{3}5W^{2}$
Beausejour	2015	Marquette + Kline	GRBC + RHG	$2W^{8}5W^{2}$
Melita	2013	Stanton + Lauder + Souris	OBC + GBC + GRBC	$4M^{4}3M^{3}3M^{3}$
Melita	2014	Newstead	OBC	3M
Melita	2015	Newstead	OBC	3M
Brandon	2013	Newdale + Varcoe + Drokan	OBC GRBC + RHG	$3T^{7}2W^{2}5W^{1}$
Brandon	2014	Newdale + Varcoe + Drokan	OBC + GRBC + RHG	$3T^{7}2W^{2}5W^{1}$
Brandon	2015	Newdale + Varcoe + Drokan	OBC + GRBC + RHG	$3T^{7}2W^{2}5W^{1}$
Carberry	2013	Wellwood	OBC	1
Carberry	2014	Ramada	OBC	1
Carberry	2015	Ramada	OBC	1
Portage	2013	Neuhorst	GRBC	2W
Portage	2014	Dugas	GRBC	2W
Portage	2015	Dugas	GRBC	2W
Roblin	2013	Erickson + Petlura + Erickson	ODGC + GDGC	$2T^{7}2W^{2}3T^{1}$
Roblin	2014	Erickson + Petlura + Erickson	ODGC + GDGC	$2T^{7}2W^{2}3T^{1}$
Roblin	2015	Erickson + Petlura + Erickson	ODGC + GDGC	$2T^{7}2W^{2}3T^{1}$
St Adolphe	2013	Scanterbury	GBC	2W
St Adolphe	2014	Scanterbury	GBC	2W
St Adolphe	2015	St. Norbert	ODGC	2D

[z] OBC: Orthic Black Chernozem, GBC: Gleyed Black Chernozem, GR: Gleyed Regosol, GRBC: Gleyed Rego Black Chernozem, PRHG: Peaty Rego Humic Glleysol, RHG: Rego Humic Gleysol, GDGC: Gleyed Dark Gray Chernozem, ODGC: Orthic Dark Grey Chernozem.

[w] Superscript numbers mean the percentile of the map unit that contains the limitation from a total of 10. The letters D, M, T and W stand for the agricultural limitations, which are soil density, moisture (droughtiness), topography and excess water, respectively.

Data obtained through the Manitoba Agriculture, Food and Rural Development.

Table B.3 Location of sites established in 2013, 2014 and 2015.

Site	Year	Legal Land Location	Latitude	Longitude
Carman	2014	NW 23-6-5 W	N 49° 29’ 717”	W 98° 02’ 409”
Carman	2015	SW 23-6-5 W	N 49° 29’ 396”	W 98° 02’ 487”
Roseisle	2014	NE 17-7-7 W	N 49° 34’ 576”	W 98° 22’ 770”
Roseisle	2015	NE 17-7-7 W	N 49° 34’ 560”	W 98° 22’ 612”
Arborg	2013	ARRL 37	N 50° 54’ 13”	W 97° 16’ 25”
Arborg	2014	ARRL 40	N 50° 54’ 221”	W 97° 15’ 105”
Arborg	2015	ARRL 41	N 50° 54’ 15”	W 97° 15’ 24”
Beausejour	2013	NE 12-13-7 E	N 50° 05’ 227”	W 96° 29’ 961”
Beausejour	2014	SE 18-13-8 E	N 50° 05’ 486”	W 96° 28’ 640”
Beausejour	2015	NE 5-13-7 E	N 50° 04’ 422”	W 96° 35’ 433”
Melita	2013	SE 36-3-28 W	N 49° 15’ 17”	W 101° 07’ 360”
Melita	2014	NE 26-3-27 W	N 49° 14’ 775”	W 101° 01’ 002”
Melita	2015	NE 26-3-27 W	N 49° 14’ 450”	W 101° 00’ 550”
Brandon	2013	SW 21-12-18 W	N 50° 01’ 26”	W 99° 53’ 19”
Brandon	2014	SW 21-12-18 W	N 50° 01’ 388”	W 99° 53’ 320”
Brandon	2015	SW 21-12-18 W	N 50° 01’ 21”	W 99° 53’ 19”
Carberry	2013	SW 8-11-14 W	N 49° 54’ 13”	W 99° 21’ 26”
Carberry	2014	SW 8-11-14 W	N 49° 54’ 369”	W 99° 21’ 116”
Carberry	2015	SW 8-11-14 W	N 49° 54’ 18”	W 99° 21’ 13”
Portage	2013	City	N 49° 57’ 379”	W 98° 16’ 079”
Portage	2014	City	N 49° 57’ 687”	W 98° 16’ 146”
Portage	2015	City	N 49° 57’ 396”	W 98° 16’ 085”
Roblin	2013	NE 20-25-28 W	N 51° 11’ 009”	W 101° 21’ 420”
Roblin	2014	NE 20-25-28 W	N 51° 10’ 988”	W 101° 21’ 679”
Roblin	2015	SE 30-25-28 W	N 51° 11’ 008”	W 101° 22’ 594”
St Adolphe	2013	NORL 25	N 49° 40’ 558”	W 97° 07’ 382”
St Adolphe	2014	NORL 31	N 49° 44’ 621”	W 97° 07’ 211”
St Adolphe	2015	NORL 32	N 49° 41’ 44”	W 97° 07’ 068”

Table B.4 Previous crop and seeder characteristics for sites established in 2013, 2014 and 2015.

Site	Year	Previous Crop	Row spacing (cm)	Opener width[z] (cm)	SBU (%)	Opener type
Carman	2014	flax	20.3	7.6	37.5	knife
Carman	2015	wheat	20.3	7.6	37.5	knife
Roseisle	2014	rye	20.3	7.6	37.5	knife
Roseisle	2015	soybean	20.3	7.6	37.5	knife
Arborg	2013	fallow	22.9	1.3	5.6	disc
Arborg	2014	wheat	22.9	1.3	5.6	disc
Arborg	2015	wheat	22.9	1.3	5.6	disc
Beausejour	2013	wheat	22.9	1.3	5.6	disc
Beausejour	2014	wheat	22.9	1.3	5.6	disc
Beausejour	2015	wheat	22.9	1.3	5.6	disc
Melita	2013	oats	24.1	1.9	7.9	knife
Melita	2014	wheat	24.1	1.9	7.9	knife
Melita	2015	flax	24.1	1.9	7.9	knife
Brandon	2013	canola	20.3	1.9	9.4	knife
Brandon	2014	barley	20.3	1.9	9.4	knife
Brandon	2015	wheat	20.3	1.9	9.4	knife
Carberry	2013	canola	30.5	2.5	8.3	disc
Carberry	2014	wheat	30.5	2.5	8.3	disc
Carberry	2015	wheat	30.5	2.5	8.3	disc
Portage	2013	potatoes	30.5	2.5	8.3	disc
Portage	2014	wheat	30.5	2.5	8.3	disc
Portage	2015	wheat	30.5	2.5	8.3	disc
Roblin	2013	wheat	22.9	2.5	11.1	knife
Roblin	2014	triticale	22.9	2.5	11.1	knife
Roblin	2015	wheat	24.1	2.5	10.5	knife
St Adolphe	2013	wheat	18.5	7.6	41.1	knife
St Adolphe	2014	wheat	18.5	7.6	41.1	knife
St Adolphe	2015	canola	18.5	7.6	41.1	knife

[z] Seed bed utilization, (SBU) = [(opener width/row spacing)*100], obtained from approximately values for row spacing and opener width.

Table B.5a Soil chemical analyses for site characterization by site in 2013.

Parameter[z]	Depth (cm)	Arborg	Beausejour	Brandon	Carberry
			2013		
pH	0-15	8.3	8.2	-	6.5
Salts (mmhols cm^{-1})	0-15	1.2	0.7	-	0.3
	15-60	1.3	3.1	-	0.4
NO_3^- - N (mg kg^{-1})	0-15	50.7	14	-	18.5
	15-60	67	72.8	-	36.8
SO_4^{2-} - S (mg kg^{-1})	0-15	120	67.5	-	20.5
	15-60	360	360	-	43.5
P (mg kg^{-1})	0-15	14	7.5	5	44.5
K (mg kg^{-1})	0-15	354.3	386	-	924.5

[z] Soil analyses developed by the Agvise laboratories at Northwood, ND. pH and salts determined by 1:1 soil:water ratio, organic matter (OM) determined by loss ignition, nitrate-N (NO_3^-) determined by cadmium reduction, sulphate-S (SO_4^{2-}) determined by turbidometric, Olsen extractable phosphorus (P) determined by sodium bicarbonate, exchangeable potassium (K) determined by ammonium acetate, carbonates determined by pressure method, and zinc determined by DTPA. Results are composed by the means of the soil test results of all the experimental blocks in each trial.

Table B.5b Soil chemical analyses for site characterization by site in 2013.

Parameter[z]	Depth (cm)	Melita	Portage	Roblin	St. Adolphe
		2013			
pH	0-15	8	8	6.7	6.7
Salts (mmhols cm^{-1})	0-15	0.1	0.6	0.2	0.5
	15-60	0.1	0.6	0.3	0.8
NO_3^- - N (mg kg^{-1})	0-15	8.7	16	14.3	19.3
	15-60	9	39	34.5	82
SO_4^{2-} - S (mg kg^{-1})	0-15	13.3	17	24	20
	15-60	28	60	42	78
P (mg kg^{-1})	0-15	3	33.8	7.3	24
K (mg kg^{-1})	0-15	136.7	471.8	175	539

[z] Soil analyses developed by the Agvise laboratories at Northwood, ND. pH and salts determined by 1:1 soil:water ratio, organic matter (OM) determined by loss ignition, nitrate-N (NO_3^-) determined by cadmium reduction, sulphate-S (SO_4^{2-}) determined by turbidometric, Olsen extractable phosphorus (P) determined by sodium bicarbonate, exchangeable potassium (K) determined by ammonium acetate, carbonates determined by pressure method, and zinc determined by DTPA. Results are composed by the means of the soil test results of all the experimental blocks in each trial.

Table B.6a Soil chemical analyses for site characterization by site in 2014.

Parameter[z]	Depth (cm)	Arborg	Beausejour	Brandon	Carberry	Carman
				2014		
pH	0-15	8	7.7	7.6	5.8	5.3
	15-60	8.1	8.1	8.1	6.7	6.5
OM (g kg^{-1})	0.-15	70	70	62	59	50
Salts (mmhols cm^{-1})	0-15	0.5	0.4	0.3	0.2	0.2
	15-60	0.6	0.8	0.3	0.4	0.2
NO_3^- - N (mg kg^{-1})	0-15	16.6	2.9	6.1	6.3	13.9
	15-60	27.6	2.8	5.8	9.5	4.8
SO_4^{2-} - S (mg kg^{-1})	0-15	12.5	6.5	3.8	4.5	5.5
	15-60	15.5	36	3.5	3.8	3.8
P (mg kg^{-1})	0-15	22.3	13.5	5.8	11.3	14.8
K (mg kg^{-1})	0-15	559.3	321.3	235.5	206	334
Zn (mg kg^{-1})	0-15	1.1	0.8	1.1	2.2	4.3
Carbonates (g kg^{-1})	0-15	124	6	7	1	2

[z] Soil analyses developed by the Agvise laboratories at Northwood, ND. pH and salts determined by 1:1 soil:water ratio, organic matter (OM) determined by loss ignition, nitrate-N (NO_3^-) determined by cadmium reduction, sulphate-S (SO_4^{2-}) determined by turbidometric, Olsen extractable phosphorus (P) determined by sodium bicarbonate, exchangeable potassium (K) determined by ammonium acetate, carbonates determined by pressure method, and zinc determined by DTPA. Results are composed by the means of the soil test results of all the experimental blocks in each trial.

Table B.6b Soil chemical analyses for site characterization by site in 2014.

Parameter[z]	Depth (cm)	Melita	Portage	Roblin	Roseisle	St. Adolphe
				2014		
pH	0-15	7.5	7.7	7	8.8	6.5
	15-60	8.1	8.2	7.9	9	7.5
OM (g kg^{-1})	0.-15	36	52	47	40	70
Salts (mmhols cm^{-1})	0-15	0.2	0.4	0.4	0.4	0.4
	15-60	0.4	0.4	0.5	0.3	0.7
NO_3^- - N (mg kg^{-1})	0-15	8.5	19.8	30.3	15.4	9.1
	15-60	6	13.5	16.9	10.4	10
SO_4^{2-} - S (mg kg^{-1})	0-15	7	5.7	7.8	27.3	7.3
	15-60	19	5	5.3	32	8.3
P (mg kg^{-1})	0-15	5	18.3	21.8	4	25
K (mg kg^{-1})	0-15	488.8	494.7	203.5	76.8	517.5
Zn (mg kg^{-1})	0-15	0.7	1.4	1.4	0.6	1.7
Carbonates (g kg^{-1})	0-15	3	9	5	93	2

[z] Soil analyses developed by the Agvise laboratories at Northwood, ND. pH and salts determined by 1:1 soil:water ratio, organic matter (OM) determined by loss ignition, nitrate-N (NO_3^-) determined by cadmium reduction, sulphate-S (SO_4^{2-}) determined by turbidometric, Olsen extractable phosphorus (P) determined by sodium bicarbonate, exchangeable potassium (K) determined by ammonium acetate, carbonates determined by pressure method, and zinc determined by DTPA. Results are composed by the means of the soil test results of all the experimental blocks in each trial.

Table B.7a Soil chemical analyses for site characterization by site in 2015.

Parameter[z]	Depth (cm)	Arborg	Beausejour	Brandon	Carberry	Carman
				2015		
pH	0-15	8.2	8	7.8	6.1	5.3
	15-60	8.3	8.1	8.3	7	7.2
OM (g kg^{-1})	0.-15	58	76	58	57	43
Salts (mmhols cm^{-1})	0-15	0.4	1	0.4	0.3	-
	15-60	0.4	2.2	0.4	0.3	-
NO_3^- - N (mg kg^{-1})	0-15	12.1	8	9.4	16.3	18.4
	15-60	5.5	4.8	2.8	7.5	10.1
SO_4^{2-} - S (mg kg^{-1})	0-15	15.3	25.8	11.5	7.5	4.3
	15-60	18.5	60+	7.5	3	3.8
P (mg kg^{-1})	0-15	13.5	10	5.3	15.3	7.3
K (mg kg^{-1})	0-15	373	442	243.3	275.8	259.3
Zn (mg kg^{-1})	0-15	0.6	1.2	1	2.1	1.9
Carbonates (g kg^{-1})	0-15	142	10	8	2	-

[z] Soil analyses developed by the Agvise laboratories at Northwood, ND. pH and salts determined by 1:1 soil:water ratio, organic matter (OM) determined by loss ignition, nitrate-N (NO_3^-) determined by cadmium reduction, sulphate-S (SO_4^{2-}) determined by turbidometric, Olsen extractable phosphorus (P) determined by sodium bicarbonate, exchangeable potassium (K) determined by ammonium acetate, carbonates determined by pressure method, and zinc determined by DTPA. Results are composed by the means of the soil test results of all the experimental blocks in each trial.

Table B.7b Soil chemical analyses for site characterization by site in 2015.

Parameter[z]	Depth (cm)	Melita	Portage	Roblin	Roseisle	St. Adolphe
				2015		
pH	0-15	7.6	7.9	6.4	8.5	6.3
	15-60	8	8.3	7.7	9	6.9
OM (g kg^{-1})	0.-15	36	59	46	32	84
Salts (mmhols cm^{-1})	0-15	0.4	0.6	0.3	-	0.9
	15-60	0.4	0.5	0.4	-	1.2
NO_3^- - N (mg kg^{-1})	0-15	17.5	12.3	10.8	17.8	21.4
	15-60	6.9	5.6	5.8	8.8	23.5
SO_4^{2-} - S (mg kg^{-1})	0-15	10	7.3	4.3	16.5	24.8
	15-60	11.3	6.3	2.8	27.3	21
P (mg kg^{-1})	0-15	7.3	10	8	4.3	71.3
K (mg kg^{-1})	0-15	436	365.3	151.3	83.3	796.8
Zn (mg kg^{-1})	0-15	0.8	1.1	1.2	0.5	3.2
Carbonates (g kg^{-1})	0-15	6	10	3	-	3

[z] Soil analyses developed by the Agvise laboratories at Northwood, ND. pH and salts determined by 1:1 soil:water ratio, organic matter (OM) determined by loss ignition, nitrate-N (NO_3^-) determined by cadmium reduction, sulphate-S (SO_4^{2-}) determined by turbidometric, Olsen extractable phosphorus (P) determined by sodium bicarbonate, exchangeable potassium (K) determined by ammonium acetate, carbonates determined by pressure method, and zinc determined by DTPA. Results are composed by the means of the soil test results of all the experimental blocks in each trial.

Appendix C

C. Repeated Measures Analyses for Plant Stand Counts (Chapter 2)

Table C.1 Effect of P fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Arborg in 2013.

Arborg 2013					
Treatment		Weeks After Planting (WAP)			
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	379	452	459	430
Seed-Placed	22.5	379	415	430	408
	45	350	393	423	389
	90	291	328	350	323
Side Band	22.5	284	379	444	369
	45	342	379	415	379
	90	401	444	496	447
Broadcast	22.5	401	430	496	442
	45	357	372	401	376
	90	321	408	474	401
Mean		350	400	439	396
ANOVA		df			*P > F*
Rate		2			0.6452
Placement		2			0.3743
Rate*Placement		4			0.0587
WAP		4			0.8852
WAP*Rate		4			0.9998
WAP*Placement		4			0.9997
Rate*Placement*WAP		8			1.0000
CV (%)					20.39

Table C.2 Effect of P fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Arborg in 2014.

Arborg 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	413	476	478	456
Seed-Placed	22.5	391	462	489	447
	45	421	484	478	461
	90	358	443	481	427
Side Band	22.5	350	407	446	401
	45	344	435	421	400
	90	459	525	563	516
Broadcast	22.5	437	503	541	494
	45	429	476	514	473
	90	424	522	519	488
Mean		403	473	493	456
ANOVA		df			*P > F*
Rate		2			0.6525
Placement		2			0.2239
Rate*Placement		4			0.0015
WAP		4			<.0001
WAP*Rate		4			0.8643
WAP*Placement		4			0.9967
Rate*Placement*WAP		8			0.9513
CV (%)					19.77

Table C.3 Effect of P fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Beausejour in 2013.

Beausejour 2013					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	348	377	407	378
Seed-Placed	22.5	367	410	421	399
	45	392	424	445	420
	90	354	410	440	401
Side Band	22.5	381	437	459	426
	45	353	402	415	390
	90	354	383	413	383
Broadcast	22.5	362	443	470	425
	45	299	322	347	323
	90	403	457	487	449
Mean		361	406	430	399
ANOVA	df				*P > F*
Rate	2				0.4506
Placement	2				0.7995
Rate*Placement	4				0.3772
WAP	4				0.2951
WAP*Rate	4				0.9401
WAP*Placement	4				0.9879
Rate*Placement*WAP	8				0.9817
CV (%)					16.77

Table C.4 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Beausejour in 2013.

Beausejour 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	375	418	421	405
Seed-Placed	22.5	366	396	405	389
	45	405	437	443	428
	90	372	375	396	381
Side Band	22.5	454	448	465	456
	45	424	416	427	422
	90	383	386	396	388
Broadcast	22.5	410	432	440	427
	45	309	394	416	373
	90	418	435	457	437
Mean		392	414	427	411
ANOVA	df				*P > F*
Rate	2				0.7327
Placement	2				0.8597
Rate*Placement	4				0.1104
WAP	4				0.2618
WAP*Rate	4				0.9433
WAP*Placement	4				0.7485
Rate*Placement*WAP	8				0.9872
CV (%)					23.51

Table C.5 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Beausejour in 2015.

Beausejour 2015				
Treatment		Weeks After Planting (WAP)		
Placement	Rate (kg P_2O_5 ha^{-1})	3	4	Mean
		Thousand plants ha^{-1}		
-	0	492	519	505
Seed-Placed	22.5	-	-	-
	45	525	549	537
	90	520	591	556
Side Band	22.5	557	579	568
	45	484	514	499
	90	423	451	437
Broadcast	22.5	462	486	474
	45	530	516	523
	90	516	552	534
Mean		501	529	515
ANOVA	df			*P > F*
Rate	2			0.7041
Placement	2			0.3924
Rate*Placement	3			0.0702
WAP	2			0.9604
WAP*Rate	2			0.9921
WAP*Placement	2			0.9951
Rate*Placement*WAP	3			0.9996
CV (%)				15.30

Table C.6 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Carberry in 2013.

Carberry 2013					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	102	282	240	208
Seed-Placed	22.5	115	257	272	215
	45	80	212	222	171
	90	50	132	147	110
Side Band	22.5	127	237	270	212
	45	112	249	229	197
	90	137	237	237	204
Broadcast	22.5	132	257	277	222
	45	125	219	247	197
	90	107	240	235	194
Mean		109	232	238	193
ANOVA	df				*P > F*
Rate	2				0.0021
Placement	2				<.0001
Rate*Placement	4				<.0001
WAP	4				0.0004
WAP*Rate	4				0.9998
WAP*Placement	4				0.0969
Rate*Placement*WAP	8				1.000
CV (%)					25.21

Table C.7 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Carberry in 2014.

Carberry 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	291	373	402	355
Seed-Placed	22.5	238	271	303	271
	45	115	197	258	190
	90	197	217	246	220
Side Band	22.5	426	480	496	467
	45	324	340	348	337
	90	369	385	393	382
Broadcast	22.5	332	340	361	344
	45	364	377	434	392
	90	336	332	385	351
Mean		299	331	363	331
ANOVA	df				*P > F*
Rate	2				0.0552
Placement	2				<.0001
Rate*Placement	4				0.0212
WAP	4				0.8163
WAP*Rate	4				0.9921
WAP*Placement	4				0.9597
Rate*Placement*WAP	8				0.9999
CV (%)					30.36

Table C.8 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Carberry in 2015.

Carberry 2015					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	137	170	174	161
Seed-Placed	22.5	189	238	244	224
	45	254	287	291	278
	90	107	141	141	130
Side Band	22.5	193	232	236	220
	45	150	185	195	176
	90	265	289	295	283
Broadcast	22.5	291	324	328	314
	45	191	252	252	232
	90	156	185	189	176
Mean		193	230	235	219
ANOVA	df				*P > F*
Rate	2				0.0552
Placement	2				0.1641
Rate*Placement	4				<.0001
WAP	4				0.1581
WAP*Rate	4				0.9789
WAP*Placement	4				0.9155
Rate*Placement*WAP	8				0.6569
CV (%)					41.52

Table C.9 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Carman in 2014.

Carman 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	579	628	637	615
Seed-Placed	22.5	605	638	665	636
	45	569	614	654	612
	90	435	484	499	472
Side Band	22.5	478	567	588	544
	45	420	487	500	469
	90	506	595	631	577
Broadcast	22.5	545	624	630	600
	45	536	594	600	577
	90	469	536	557	521
Mean		514	577	596	562
ANOVA	df				*P > F*
Rate	2				0.2888
Placement	2				0.6465
Rate*Placement	4				<.0001
WAP	4				<.0001
WAP*Rate	4				0.9803
WAP*Placement	4				0.4432
Rate*Placement*WAP	8				0.9983
CV (%)					18.96

Table C.10 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Carman in 2015.

Carman 2015					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	255	504	526	428
Seed-Placed	22.5	301	492	518	437
	45	221	512	510	415
	90	177	452	461	363
Side Band	22.5	252	506	518	425
	45	267	509	532	436
	90	307	606	627	513
Broadcast	22.5	148	484	503	378
	45	271	529	535	445
	90	327	530	567	475
Mean		253	512	530	432
ANOVA	df				*P > F*
Rate	2				0.4522
Placement	2				0.2091
Rate*Placement	4				0.0522
WAP	4				<.0001
WAP*Rate	4				0.9872
WAP*Placement	4				0.9857
Rate*Placement*WAP	8				0.6237
CV (%)					34.82

Table C.11 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Melita in 2013.

Melita 2013					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	483	424	618	508
Seed-Placed	22.5	573	417	396	462
	45	470	312	403	395
	90	332	153	181	222
Side Band	22.5	456	333	424	404
	45	421	472	382	425
	90	504	493	437	478
Broadcast	22.5	463	361	528	451
	45	359	389	451	400
	90	428	396	604	476
Mean		449	375	442	422
ANOVA	df				*P > F*
Rate	2				0.0352
Placement	2				0.0009
Rate*Placement	4				<.0001
WAP	4				0.8635
WAP*Rate	4				0.9941
WAP*Placement	4				0.8067
Rate*Placement*WAP	8				0.9996
CV (%)					31.92

Table C.12 Effect of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Melita in 2014.

Melita 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	286	281	286	284
Seed-Placed	22.5	332	286	332	317
	45	289	284	330	301
	90	370	313	334	339
Side Band	22.5	386	402	438	408
	45	299	309	330	313
	90	382	403	392	392
Broadcast	22.5	295	352	362	337
	45	275	280	326	294
	90	320	268	310	299
Mean		323	318	344	328
ANOVA	df				*P > F*
Rate	2				0.9463
Placement	2				0.8115
Rate*Placement	4				0.9954
WAP	4				0.0990
WAP*Rate	4				0.1402
WAP*Placement	4				0.4262
Rate*Placement*WAP	8				0.6616
CV (%)					23.90

Table C.13 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Melita in 2015.

Melita 2015					
Treatment		Weeks After Planting (WAP)			
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	47	293	324	221
Seed-Placed	22.5	47	365	378	263
	45	52	370	409	277
	90	52	308	323	228
Side Band	22.5	67	329	349	249
	45	44	342	388	258
	90	44	292	318	218
Broadcast	22.5	67	308	326	234
	45	62	349	387	266
	90	60	272	318	217
Mean		54	323	352	243
ANOVA	df				*P > F*
Rate	2				0.2815
Placement	2				0.8476
Rate*Placement	4				0.9017
WAP	4				<.0001
WAP*Rate	4				0.9869
WAP*Placement	4				0.9560
Rate*Placement*WAP	8				0.9999
CV (%)					59.28

Table C.14 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Roseisle in 2014.

Roseisle 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	394	455	520	456
Seed-Placed	22.5	437	498	590	508
	45	446	504	603	518
	90	489	563	664	572
Side Band	22.5	394	434	489	439
	45	357	430	477	421
	90	375	434	464	424
Broadcast	22.5	486	510	581	526
	45	430	461	587	493
	90	504	544	692	580
Mean		431	483	567	494
ANOVA	df				*P > F*
Rate	2				0.4023
Placement	2				0.0050
Rate*Placement	4				0.8353
WAP	4				0.7140
WAP*Rate	4				0.9999
WAP*Placement	4				0.9995
Rate*Placement*WAP	8				1.000
CV (%)					22.09

Table C.15 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Roseisle in 2015.

Roseisle 2015					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	532	715	746	664
Seed-Placed	22.5	577	694	726	665
	45	431	535	569	512
	90	426	653	693	591
Side Band	22.5	417	547	600	521
	45	449	632	633	571
	90	486	600	626	570
Broadcast	22.5	391	671	700	587
	45	494	618	669	594
	90	478	653	670	601
Mean		468	632	663	588
ANOVA	df				*P > F*
Rate	2				0.5695
Placement	2				0.4356
Rate*Placement	4				0.1485
WAP	4				0.3849
WAP*Rate	4				0.9998
WAP*Placement	4				0.9996
Rate*Placement*WAP	8				1.000
CV (%)					21.00

Table C.16 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Brandon in 2013.

Brandon 2013					
Treatment		Weeks After Planting (WAP)			
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	411	423	442	425
Seed-Placed	22.5	429	448	423	433
	45	442	510	461	471
	90	458	513	464	478
Side Band	22.5	460	503	491	485
	45	430	461	412	435
	90	460	490	472	474
Broadcast	22.5	418	424	418	420
	45	485	492	467	481
	90	418	492	436	449
Mean		441	476	449	455
ANOVA	df				*P > F*
Rate	2				0.6880
Placement	2				0.8491
Rate*Placement	4				0.2127
WAP	4				0.1480
WAP*Rate	4				0.9097
WAP*Placement	4				0.9936
Rate*Placement*WAP	8				0.9655
CV (%)					16.35

Table C.17 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Brandon in 2014.

Brandon 2014					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	535	547	593	559
Seed-Placed	22.5	560	634	643	612
	45	490	536	569	532
	90	381	439	457	426
Side Band	22.5	522	586	577	562
	45	523	572	606	567
	90	525	571	577	558
Broadcast	22.5	474	596	612	561
	45	551	557	572	560
	90	507	559	553	540
Mean		507	560	576	548
ANOVA	df				*P > F*
Rate	2				0.0899
Placement	2				0.4060
Rate*Placement	4				0.1917
WAP	4				0.5035
WAP*Rate	4				0.9390
WAP*Placement	4				0.9965
Rate*Placement*WAP	8				0.9998
CV (%)					16.45

Table C.18 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Brandon in 2015.

Brandon 2015					
Treatment		Weeks After Planting (WAP)			
Placement	Rate (kg P_2O_5 ha^{-1})	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	375	458	431	421
Seed-Placed	22.5	397	458	474	443
	45	443	504	498	482
	90	344	406	403	384
Side Band	22.5	375	415	434	408
	45	486	508	547	514
	90	354	434	409	399
Broadcast	22.5	311	391	388	363
	45	363	452	449	421
	90	360	406	412	393
Mean		381	443	444	423
ANOVA	df				*P > F*
Rate	2				0.0409
Placement	2				0.0659
Rate*Placement	4				0.4056
WAP	4				0.0153
WAP*Rate	4				0.9967
WAP*Placement	4				0.9872
Rate*Placement*WAP	8				0.9991
CV (%)					25.21

Table C.19 Effects of phosphorus fertilization on plant stand counts at 2, 3 and 4 weeks after planting, at Roblin in 2015.

Roblin 2015					
Treatment		Weeks After Planting (WAP)			
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2	3	4	Mean
		Thousand plants ha^{-1}			
-	0	427	445	463	445
Seed-Placed	22.5	384	400	413	399
	45	332	350	366	349
	90	238	264	277	259
Side Band	22.5	411	439	465	438
	45	396	411	435	414
	90	424	442	452	440
Broadcast	22.5	409	452	475	445
	45	339	352	372	354
	90	471	487	526	494
Mean		383	404	424	404
ANOVA	df				*P > F*
Rate	2				0.1544
Placement	2				0.0026
Rate*Placement	4				0.0012
WAP	4				0.0401
WAP*Rate	4				0.9977
WAP*Placement	4				0.9976
Rate*Placement*WAP	8				0.9990
CV (%)					21.80

Appendix D

D. Plant Tissue Phosphorus Concentration (Chapter 2)

Table D.1 Plant tissue phosphorus concentration as affected by rate and placement of monoammonium phosphate, by site in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2013					
		Plant Tissue P Concentration (g kg^{-1})					
-	0	2.1	2.9	1.9	3.6	2.6	2.6
Seed-Placed	22.5	2.3	3.2	2.0	3.8	2.9	2.5
	45	2.5	3.0	2.1	3.8	2.8	2.6
	90	2.6	3.5	2.3	3.8	3.7	-
Side Band	22.5	2.4	2.9	2.0	3.6	2.9	-
	45	2.7	2.9	2.1	3.8	2.7	-
	90	2.8	3.5	2.0	3.8	3.1	-
Broadcast	22.5	2.4	2.9	2.1	3.5	2.9	2.5
	45	2.2	2.9	2.2	3.8	3.2	2.7
	90	2.5	3.0	2.4	3.7	3.4	-
Mean		2.4	3.1	2.1	3.7	3.0	2.6
ANOVA		*P > F*					
Rate		0.0033	0.3653	0.0785	0.2487	0.0700	0.1755
Placement		0.0129	0.1291	0.0510	0.2375	0.0332	0.8722
Rate*Placement		0.1808	0.4654	0.4247	0.3699	0.0671	0.8722
CV (%)		11.13	13.51	11.16	6.48	13.32	15.86

Table D.2a Plant tissue phosphorus concentration as affected by rate and placement of monoammonium phosphate, by site in 2014.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		Plant Tissue P Concentration (g kg^{-1})				
-	0	2.5	2.4	2.0	2.1	2.8
Seed-Placed	22.5	2.7	2.4	2.0	2.1	3.2
	45	2.6	2.3	2.0	2.1	3.2
	90	2.9	2.3	2.2	2.3	3.5
Side Band	22.5	2.4	2.3	2.0	2.3	3.2
	45	2.7	2.2	2.1	2.2	3.1
	90	2.9	2.1	2.2	2.3	3.5
Broadcast	22.5	2.7	2.2	1.9	2.3	3.0
	45	2.9	2.2	2.0	2.1	3.1
	90	2.8	2.4	1.9	2.2	3.6
Mean		2.7	2.3	2.0	2.2	3.2
ANOVA		*P > F*				
Rate		0.0839	0.9712	0.3201	0.1934	0.0073
Placement		0.4048	0.3904	0.1471	0.5449	0.8459
Rate*Placement		0.3230	0.3452	0.6543	0.6655	0.8890
CV (%)		10.69	9.06	9.85	12.74	11.74

Table D.2b Plant tissue phosphorus concentration as affected by rate and placement of monoammonium phosphate, by site in 2014.

Treatment		Carman	Roseisle
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014 Plant Tissue P Concentration ($g\ kg^{-1}$)	
-	0	2.3	2.0
Seed-Placed	22.5	2.3	2.2
	45	2.5	2.4
	90	2.3	2.5
Side Band	22.5	2.3	2.5
	45	2.3	2.2
	90	2.3	2.6
Broadcast	22.5	2.3	2.1
	45	2.2	2.2
	90	2.5	2.2
Mean		2.3	2.3
ANOVA		*P > F*	
Rate		0.7709	0.0166
Placement		0.8091	0.0024
Rate*Placement		0.3691	0.0755
CV (%)		9.53	10.87

Table D.3a Plant tissue phosphorus concentration as affected by rate and placement of monoammonium phosphate, by site in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2015				
		Plant Tissue P Concentration ($g\ kg^{-1}$)				
-	0	2.4	2.7	2.8	2.7	2.2
Seed-Placed	22.5	2.4	2.6	-	2.7	2.4
	45	2.8	2.6	2.8	2.8	2.6
	90	2.9	2.4	2.7	2.7	2.9
Side Band	22.5	2.6	2.6	2.5	2.9	2.4
	45	2.6	2.5	2.5	2.8	2.5
	90	3.0	2.6	2.6	2.9	2.7
Broadcast	22.5	2.4	2.5	2.6	3.0	2.2
	45	2.8	2.4	2.7	2.7	2.4
	90	2.9	2.5	2.9	2.9	2.6
Mean		2.7	2.5	2.7	2.8	2.5
ANOVA		*P > F*				
Rate		0.0004	0.7423	0.2395	0.4384	<.0001
Placement		0.9384	0.7196	0.0916	0.0490	0.0011
Rate*Placement		0.2774	0.5797	0.5189	0.4862	0.6199
CV (%)		18.31	12.04	11.36	7.59	9.54

Table D.3b Plant tissue phosphorus concentration as affected by rate and placement of monoammonium phosphate, by site in 2015.

Treatment		Carman	Roseisle	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2015		
		Plant Tissue P Concentration (g kg^{-1})		
-	0	2.1	1.8	2.8
Seed-Placed	22.5	2.3	2.1	2.7
	45	2.2	2.2	2.7
	90	2.4	2.4	3.0
Side Band	22.5	2.3	1.8	3.0
	45	2.3	2.2	2.9
	90	2.2	2.4	2.8
Broadcast	22.5	2.4	2.1	3.0
	45	2.4	2.1	2.9
	90	2.7	2.4	3.0
Mean		2.3	2.1	2.9
ANOVA		*P > F*		
Rate		0.1019	0.0001	0.7405
Placement		0.0033	0.1240	0.4419
Rate*Placement		0.3159	0.0827	0.2905
CV (%)		9.36	11.34	11.71

Appendix E

E. Plant Tissue Phosphorus Uptake (Chapter 2)

Table E.1a Mid-season biomass (R3) phosphorus uptake as affected by monoammonium phosphate rate and placement, by site in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry
Placement	Rate (kg P_2O_5 ha^{-1})	2013			
		Biomass P uptake (kg ha^{-1})			
-	0	11.4	14.2	10.8*ab*	22.8
Seed-Placed	22.5	14.7	18.1	9.6*ab*	22.5
	45	13.5	16.0	11.5*a*	18.9
	90	14.4	13.9	10.4*ab*	22.9
Side Band	22.5	12.6	18.0	10.1*ab*	27.6
	45	12.7	15.5	10.7*ab*	24.9
	90	15.8	14.1	9.5*ab*	25.3
Broadcast	22.5	10.8	15.6	9.7*ab*	24.1
	45	11.9	13.3	7.5*b*	25.4
	90	15.6	12.4	12.6*a*	25.5
Mean		13.3	15.1	10.2	24.0
ANOVA		$P > F$			
Rate		0.0104	0.7489	0.4090	0.4744
Placement		0.2893	0.1368	0.6273	0.0559
Rate*Placement		0.2741	0.0947	0.0043	0.8466
CV(%)		20.77	19.89	21.89	20.12

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table E.1b Mid-season biomass (R3) phosphorus uptake as affected by monoammonium phosphate rate and placement, by site in 2013.

Treatment		Melita	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2013	
		Biomass P uptake (kg ha^{-1})	
-	0	18.1	18.6
Seed-Placed	22.5	16.3	15.5
	45	15.7	18.9
	90	10.4	-
Side Band	22.5	14.1	-
	45	9.0*b*	-
	90	15.0	-
Broadcast	22.5	18.2	19.5
	45	17.8	17.8
	90	23.9	-
Mean		15.9	18.1
ANOVA		*P > F*	
Rate		0.4849	0.6111
Placement		0.0054	0.3479
Rate*Placement		0.1070	0.1195
CV(%)		34.90	26.85

Table E.2a Mid-season biomass (R3) phosphorus uptake as affected by monoammonium phosphate rate and placement, by site in 2014.

Treatment		Brandon	Arborg	Beausejour	Carberry
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014			
		Biomass P uptake ($kg\ ha^{-1}$)			
-	0	5.6*b*	8.5	6.5	9.1
Seed-Placed	22.5	6.3*ab*	8.1	5.8	6.5
	45	7.4*ab*	10.2	7.1	6.9
	90	6.0*b*	9.7	5.4	8.6
Side Band	22.5	5.8*b*	8.2	6.9	11.6
	45	6.5*ab*	8.4	7.7	9.7
	90	8.4*a*	9.3	7.6	10.3
Broadcast	22.5	6.8*ab*	9.7	6.2	9.4
	45	6.7*ab*	8.8	6.0	8.8
	90	6.2*ab*	9.4	7.5	9.0
Mean		6.6	9.0	6.7	9.0
ANOVA		$P > F$			
Rate		0.2818	0.4597	0.6037	0.6269
Placement		0.5859	0.4577	0.1352	0.0063
Rate*Placement		0.0046	0.4067	0.4014	0.6176
CV(%)		17.49	20.22	20.06	31.70

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table E.2b Mid-season biomass (R3) phosphorus uptake as affected by monoammonium phosphate rate and placement, by site in 2014.

Treatment		Melita	Carman	Roseisle
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014		
		Biomass P uptake ($kg\ ha^{-1}$)		
-	0	8.5	9.4	4.8
Seed-Placed	22.5	11.5	7.9	6.4
	45	11.6	9.9	5.6
	90	9.7	8.1	6.5
Side Band	22.5	12.6	9.0	5.9
	45	11.2	10.0	5.7
	90	12.6	10.2	7.9
Broadcast	22.5	11.4	9.5	5.6
	45	8.7	8.4	5.2
	90	11.5	12.8	6.2
Mean		10.9	9.5	6.0
ANOVA		$P > F$		
Rate		0.3526	0.3324	0.0647
Placement		0.2111	0.3107	0.3926
Rate*Placement		0.3593	0.2087	0.7423
CV(%)		23.01	27.89	24.84

Table E.3a Mid-season biomass (R3) phosphorus uptake as affected by monoammonium phosphate rate and placement, by site in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry
Placement	Rate (kg P_2O_5 ha^{-1})	2015			
		Biomass P uptake (kg ha^{-1})			
-	0	8.5	6.3	13.2	8.7
Seed-Placed	22.5	9.0	5.4	-	7.8
	45	10.1	6.7	13.1	11.4
	90	8.1	6.6	7.5	7.3
Side Band	22.5	9.9	7.1	12.5	8.4
	45	10.9	6.6	13.0	10.0
	90	8.8	7.2	10.9	10.8
Broadcast	22.5	6.1	6.8	14.1	10.7
	45	10.0	8.0	14.5	9.7
	90	7.0	8.4	17.0	9.5
Mean		8.8	6.9	12.9	9.4
ANOVA		*P > F*			
Rate		0.0651	0.5553	0.5832	0.5784
Placement		0.1223	0.2758	0.0492	0.7243
Rate*Placement		0.7812	0.9268	0.2856	0.5295
CV(%)		34.65	33.63	33.00	36.38

Table E.3b Mid-season biomass (R3) phosphorus uptake as affected by monoammonium phosphate rate and placement, by site in 2015.

Treatment		Melita	Carman	Roseisle	Roblin
Placement	Rate (kg P_2O_5 ha^{-1})	2015			
		Biomass P uptake (kg ha^{-1})			
-	0	8.2	6.3	7.9	9.2
Seed-Placed	22.5	10.6	9.7	6.8	9.0
	45	9.6	9.1	7.4	7.8
	90	11.5	9.8	9.8	7.6
Side Band	22.5	10.2	9.5	6.6	9.3
	45	8.8	10.9	7.6	9.4
	90	9.0	10.0	8.6	10.3
Broadcast	22.5	10.5	9.7	7.7	8.9
	45	11.2	9.2	8.6	8.6
	90	9.4	11.2	8.7	8.4
Mean		9.9	9.5	8.0	8.8
ANOVA		*P > F*			
Rate		0.7416	0.7118	0.0472	0.6628
Placement		0.2505	0.7693	0.6646	0.0151
Rate*Placement		0.3373	0.7218	0.7629	0.4076
CV(%)		20.35	26.53	25.45	20.25

Appendix F

F. Seed Phosphorus Concentration (Chapter 2)

Table F.1a Effects of phosphorus rate and placement on seed phosphorus concentration by location in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013				
		Seed P Concentration (g kg^{-1})				
-	0	4.4	6.8	5.0	6.7	5.0*b*
Seed-Placed	22.5	4.9	6.9	4.9	6.7	5.3*b*
	45	4.8	6.8	5.2	6.7	5.2*b*
	90	5.6	6.5	5.4	7.1	6.2*a*
Side Band	22.5	4.9	7.0	4.8	6.7	5.2*b*
	45	5.3	6.7	5.1	6.7	5.2*b*
	90	5.7	6.7	5.0	6.7	5.3*b*
Broadcast	22.5	4.8	6.5	4.9	6.8	5.3*b*
	45	5.0	6.7	5.4	6.7	5.4*b*
	90	5.6	6.7	5.4	6.8	5.3*b*
Mean		5.1	6.7	5.1	6.8	5.3
ANOVA		*P > F*				
Rate		0.0002	0.7164	0.0446	0.3410	0.012
Placement		0.3729	0.4241	0.0060	0.4615	0.0576
Rate*Placement		0.7366	0.3135	0.2161	0.6071	0.0080
CV (%)		10.92	4.65	6.38	4.21	7.02

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table F.1b Effects of phosphorus rate and placement on seed phosphorus concentration by location in 2013.

Treatment		Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2013		
		Seed P Concentration (g kg^{-1})		
-	0	5.2	6.8	5.3
Seed-Placed	22.5	5.2	7.1	5.1
	45	5.2	6.9	5.3
Broadcast	22.5	5.1	7.0	5.6
	45	5.2	6.5	5.6
Mean		5.2	6.9	5.4
ANOVA		*P > F*		
Rate		0.6848	0.1449	0.5337
Placement		0.2156	0.1839	0.0106
Rate*Placement		0.4711	0.2974	0.7883
CV (%)		12.63	5.62	5.89

Table F.2a Effects of phosphorus rate and placement on seed phosphorus concentration by location in 2014.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		Seed P Concentration (g kg^{-1})				
-	0	4.2	5.0	4.1	4.2	3.8
Seed-Placed	22.5	4.6	5.3	4.0	4.1	4.1
	45	4.8	5.3	4.5	4.1	4.4
	90	5.3	5.4	4.5	4.4	4.8
Side Band	22.5	4.9	5.1	4.2	4.5	4.2
	45	4.8	5.2	4.1	4.0	4.6
	90	5.3	5.2	4.3	4.5	5.3
Broadcast	22.5	4.7	5.2	4.0	4.4	4.4
	45	4.9	5.0	4.3	4.2	4.6
	90	4.9	5.3	4.3	4.1	4.7
Mean		4.8	5.2	4.2	4.2	4.5
ANOVA		*P > F*				
Rate		0.0056	0.4229	0.0119	0.1109	<.0001
Placement		0.4503	0.4989	0.2637	0.6758	0.1060
Rate*Placement		0.3947	0.9005	0.1997	0.2598	0.0916
CV (%)		9.53	5.92	8.03	10.53	10.44

Table F.2b Effects of phosphorus rate and placement on seed phosphorus concentration by location in 2014.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		Seed P Concentration (g kg^{-1})				
-	0	4.7	4.0	5.8	6.1	4.7
Seed-Placed	22.5	4.7	4.2	5.5	6.2	4.8
	45	5.0	4.6	5.5	6.3	4.8
	90	5.1	4.7	5.6	6.3	4.7
Side Band	22.5	4.8	4.5	-	-	-
	45	4.5	4.3	-	-	-
	90	4.7	4.8	-	-	-
Broadcast	22.5	4.7	4.1	5.7	5.9	4.8
	45	4.7	4.2	5.9	5.9	4.8
	90	4.9	4.1	5.8	5.8	5.0
Mean		4.8	4.4	5.7	6.1	4.8
ANOVA		*P > F*				
Rate		0.0763	0.2653	0.5638	0.9841	0.6128
Placement		0.0150	0.0418	0.0381	0.0287	0.5226
Rate*Placement		0.1797	0.3871	0.6477	0.9189	0.5575
CV (%)		6.30	11.96	5.73	6.97	5.85

Table F.3a. Effects of phosphorus rate and placement on seed phosphorus concentration by location in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Seed P Concentration (g kg^{-1})				
-	0	4.1	6.6	4.8	5.4*a*	4.4
Seed-Placed	22.5	4.1	6.4	-	5.4*a*	4.7
	45	4.3	6.4	5.0	5.9*a*	5.0
	90	4.9	6.3	5.0	6.0*a*	5.2
Side Band	22.5	4.2	6.4	4.5	5.4*a*	5.0
	45	4.2	6.4	4.9	5.6*a*	4.9
	90	4.8	6.6	4.5	5.6*a*	5.2
Broadcast	22.5	4.1	6.4	4.7	5.8*a*	4.6
	45	4.5	6.7	4.9	5.6*a*	4.9
	90	4.9	6.8	5.0	5.5*a*	5.0
Mean		4.4	6.5	4.8	5.6	4.9
ANOVA		*P > F*				
Rate		<.0001	0.5272	0.5632	0.3001	0.1050
Placement		0.6297	0.3864	0.2230	0.4391	0.4663
Rate*Placement		0.8161	0.7328	0.6152	0.0387	0.8159
CV (%)		12.69	6.23	8.65	6.49	8.46

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table F.3b Effects of phosphorus rate and placement on seed phosphorus concentration by location in 2015.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Seed P Concentration (g kg^{-1})				
-	0	4.2	3.2	5.5	5.1	5.1
Seed-Placed	22.5	4.5	4.0	5.4	5.2	5.0
	45	4.2	3.9	5.4	5.3	4.8
	90	4.4	4.7	5.9	5.4	5.2
Side Band	22.5	3.8	3.4	4.9	-	-
	45	4.2	4.1	5.2	-	-
	90	4.2	4.2	5.6	-	-
Broadcast	22.5	3.9	3.8	5.2	5.3	4.6
	45	3.8	3.8	5.3	5.4	4.8
	90	4.3	4.3	5.4	5.2	4.9
Mean		4.1	3.9	5.4	5.3	4.9
ANOVA		*P > F*				
Rate		0.1523	<.0001	0.0008	0.8509	0.5405
Placement		0.0373	0.1158	0.0139	0.9515	0.2087
Rate*Placement		0.1872	0.2068	0.4386	0.4171	0.6085
CV (%)		9.23	12.87	6.66	5.98	8.57

Appendix G

G. Seed Phosphorus Uptake (Chapter 2)

Table G.1a Seed phosphorus uptake as affected phosphorus fertilizer rate and placement, by site in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013				
		Seed P Uptake (kg ha^{-1})				
-	0	10.4*b*	16.1*ab*	19.2	23.6*a*	19.7
Seed-Placed	22.5	10.4*b*	18.5*ab*	19.8	24.6*a*	19.8
	45	10.9*b*	17.2*ab*	21.8	21.2*ab*	19.4
	90	10.2*b*	15.6*b*	23.2	17.8*b*	15.7
Side Band	22.5	10.8*b*	16.9*ab*	18.2	22.8*a*	16.9
	45	11.3*ab*	16.3*ab*	20.1	22.2*ab*	17.9
	90	10.5*b*	17.7*ab*	19.9	21.4*ab*	19.8
Broadcast	22.5	11.3*ab*	17.8*ab*	19.7	21.4*ab*	19.1
	45	11.2*ab*	17.4*ab*	22.2	23.8*a*	20.3
	90	13.2*a*	20.0*a*	21.9	21.7*ab*	20.1
Mean		11.0	17.3	20.6	22.0	18.9
ANOVA		$P > F$				
Rate		0.3845	0.6537	0.0720	0.0407	0.8559
Placement		0.0009	0.0901	0.0215	0.2952	0.1509
Rate*Placement		0.0098	0.0626	0.8896	0.0242	0.0513
CV (%)		10.18	12.75	19.75	20.25	15.33

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table G.1b Seed phosphorus uptake as affected phosphorus fertilizer rate and placement, by site in 2013.

Treatment		Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2013		
		Seed P Uptake (kg ha^{-1})		
-	0	8.0	21.6	23.5
Seed-Placed	22.5	8.7	20.4	23.8
	45	7.9	20.8	25.5
Broadcast	22.5	8.4	22.2	23.9
	45	8.5	19.5	25.6
Mean		8.3	20.9	24.5
ANOVA		*P > F*		
Rate		0.5825	0.4084	0.0263
Placement		0.7492	0.8692	0.851
Rate*Placement		0.2572	0.2579	0.9925
CV (%)		13.33	11.88	7.61

Table G.2a Seed phosphorus uptake as affected phosphorus fertilizer rate and placement, by site in 2014.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		Seed P Uptake (kg ha^{-1})				
-	0	4.8	17.6	10.0	12.4	13.4
Seed-Placed	22.5	5.9	18.9	10.1	13.4	14.1
	45	5.9	19.2	10.3	12.4	15.0
	90	5.1	19.5	10.3	12.6	15.4
Side Band	22.5	6.6	18.3	9.6	15.3	15.7
	45	6.5	19.3	10.3	13.8	16.8
	90	7.3	20.1	10.4	14.7	17.0
Broadcast	22.5	5.6	19.5	9.6	14.9	14.6
	45	6.2	16.7	10.1	13.2	15.1
	90	6.5	18.5	10.8	13.6	16.8
Mean		6.0	18.8	10.2	13.6	15.4
ANOVA		*P > F*				
Rate		0.6778	0.3568	0.2481	0.1837	0.1244
Placement		0.0034	0.2416	0.9472	0.0694	0.0982
Rate*Placement		0.1525	0.1743	0.9336	0.9845	0.9178
CV (%)		16.95	1.69	11.32	21.62	12.93

Table G.2b Seed phosphorus uptake as affected phosphorus fertilizer rate and placement, by site in 2014.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014				
		Seed P Uptake ($kg\ ha^{-1}$)				
-	0	16.7	8.5	13.5	24.8	9.9
Seed-Placed	22.5	16.7	10.7	11.2	23.2	9.9
	45	17.4	12.3	11.6	23.2	10.1
	90	16.8	11.1	10.6	21.1	11
Side Band	22.5	16.7	9.9	-	-	-
	45	15.7	11	-	-	-
	90	17.2	11.5	-	-	-
Broadcast	22.5	17	9.7	12.5	24.1	10.5
	45	16.9	10.3	12.1	23.5	11.2
	90	16.4	10.8	12.1	22.7	12
Mean		16.8	10.6	11.9	23.2	10.6
ANOVA		*P > F*				
Rate		0.9419	0.0604	0.837	0.484	0.1289
Placement		0.626	0.095	0.2108	0.4742	0.0989
Rate*Placement		0.3066	0.5741	0.868	0.9152	0.9133
CV (%)		6.44	14.76	25.44	12.36	12.74

Table G.3a Seed phosphorus uptake as affected phosphorus fertilizer rate and placement, by site in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Seed P Uptake (kg ha^{-1})				
-	0	12.5	16.2	21	17	13.9
Seed-Placed	22.5	12	14.8	-	18.5	16.3
	45	14.3	15.4	21.6	23.4	16.3
	90	17.8	15.9	24.8	18.6	17.5
Side Band	22.5	14.1	15.5	20.5	20.8	16.9
	45	15.3	16	19.8	20.7	15.8
	90	18.5	16	20.7	25.2	18.2
Broadcast	22.5	12.7	16.8	22.1	23.3	15.3
	45	15.2	17.6	22.4	21.3	16.4
	90	15.2	16.7	23.8	19.7	16.3
Mean		14.7	16.1	21.9	20.8	16.3
ANOVA		*P > F*				
Rate		0.0019	0.5256	0.3059	0.8362	0.1200
Placement		0.2574	0.0197	0.0711	0.3910	0.3149
Rate*Placement		0.6214	0.8711	0.8369	0.0734	0.5724
CV (%)		26.71	12.87	13.27	18.78	10.91

Table G.3b Seed phosphorus uptake as affected phosphorus fertilizer rate and placement, by site in 2015.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Seed P Uptake (kg ha^{-1})				
-	0	12.9	8.2	16.7	22.1	18.6
Seed-Placed	22.5	14.9	11.0	16.1	23.8	19.4
	45	14.0	11.5	14.1	23.9	18.3
	90	16.5	13.8	13.8	24.7	20.2
Side Band	22.5	12.0	9.2	15.2	-	-
	45	12.5	11.8	15.9	-	-
	90	14.4	12.9	18.0	-	-
Broadcast	22.5	11.9	10.5	15.7	24.3	17.5
	45	13.1	11.3	15.3	25.5	18.6
	90	13.5	13.1	16.4	23.1	18.7
Mean		13.6	11.3	15.7	23.9	18.8
ANOVA		*P > F*				
Rate		0.0134	<.0001	0.4832	0.6938	0.4168
Placement		0.0010	0.3233	0.1116	0.8386	0.1752
Rate*Placement		0.5828	0.5850	0.1465	0.2816	0.4142
CV (%)		14.15	20.12	15.37	8.63	9.68

Appendix H

H. Seed Protein Concentration (Chapter 2)

Table H.1a Effects of phosphorus fertilizer rate and placement on seed protein concentration, by site in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2013				
		Protein ($g\ kg^{-1}$)				
-	0	384	306*ab*	369	389	376
-	22.5	383	303*ab*	368	386	373
-	45	383	297*b*	366	384	372
-	90	385	320*a*	369	387	376
-	0	384	306	369	389	376
Seed-Placed	-	384	310	369	387	373
Side-Band	-	384	305	367	385	373
Broadcast	-	384	305	367	386	374
-	0	384	306	369	389	376
Seed-Placed	22.5	384	306	369	385	372
	45	385	301	368	387	370
	90	384	323	369	388	377
Side Band	22.5	382	304	368	388	371
	45	384	296	365	382	374
	90	385	314	368	385	374
Broadcast	22.5	384	299	367	386	375
	45	381	295	365	384	372
	90	385	323	370	388	377
Mean		384	307	368	386	374
ANOVA		$P > F$				
Rate		0.3111	0.0124	0.0703	0.3028	0.1669
Placement		0.9148	0.1157	0.2960	0.6701	0.7203
Rate*Placement		0.3922	0.3564	0.7834	0.3763	0.6133
CV (%)		0.79	5.06	0.98	1.47	1.49

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table H.1b Effects of phosphorus fertilizer rate and placement on seed protein concentration, by site in 2013.

Treatment		Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2013		
		Protein (g kg^{-1})		
-	0	383	359	364
-	22.5	380	361	365
-	45	375	359	364
-	0	383	359	364
Seed-Placed	-	377	361	363
Broadcast	-	378	360	365
-	0	383	359	364
Seed-Placed	22.5	379	362	363
	45	375	360	363
Broadcast	22.5	380	360	367
	45	375	359	364
	90	-	-	-
Mean		379	360	364
ANOVA		*P > F*		
Rate		0.1838	0.5957	0.4806
Placement		0.6358	0.6074	0.2637
Rate*Placement		0.7130	0.9578	0.4059
CV (%)		1.44	1.29	0.91

Table H.2a Effects of phosphorus fertilizer rate and placement on seed protein concentration, by site in 2014.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014				
		Protein ($g\ kg^{-1}$)				
-	0	364	347	348	338	356
-	22.5	367	344	347	337	357
-	45	369	345	349	338	356
-	90	368	342	347	336	354
-	0	364	347	348	338	356
Seed-Placed	-	369	346	348	337	356
Side-Band	-	368	342	348	336	354
Broadcast	-	367	342	348	338	356
-	0	364	347*a*	348	338	356
Seed-Placed	22.5	367	346*ab*	347	339	357
	45	369	347*a*	349	336	356
	90	371	346*ab*	347	336	356
Side Band	22.5	367	343*ab*	349	336	357
	45	369	340*ab*	347	338	355
	90	367	342*ab*	347	334	350
Broadcast	22.5	366	342*ab*	345	335	355
	45	369	347*a*	350	340	357
	90	367	337*b*	347	339	357
Mean		368	344	348	337	356
ANOVA		$P > F$				
Rate		0.1007	0.3018	0.2073	0.4911	0.6015
Placement		0.3088	0.0104	0.9900	0.5460	0.6055
Rate*Placement		0.6689	0.0434	0.3141	0.2552	0.5599
CV (%)		0.87	1.88	0.86	1.15	1.43

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table H.2b Effects of phosphorus fertilizer rate and placement on seed protein concentration, by site in 2014.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2014				
		Protein (g kg^{-1})				
-	0	339	340	362	347	351
-	22.5	338	335	363	348	355
-	45	339	332	362	348	352
-	90	338	336	362	346	352
-	0	339	340	362	347	351
Seed-Placed	-	339	338	363	346	352
Side-Band	-	339	333	-	-	-
Broadcast	-	337	331	362	348	354
-	0	339	340	362	347	351
Seed-Placed	22.5	338	334	363	346	357
	45	341	340	363	347	351
	90	339	341	363	346	349
Side Band	22.5	338	336	-	-	-
	45	339	325	-	-	-
	90	339	339	-	-	-
Broadcast	22.5	338	336	363	350	354
	45	338	331	361	348	353
	90	336	327	362	346	354
Mean		338	335	362	347	353
ANOVA		*P > F*				
Rate		0.6556	0.5923	0.8827	0.4656	0.4496
Placement		0.1758	0.2227	0.6549	0.2642	0.5771
Rate*Placement		0.8687	0.2339	0.7894	0.5425	0.3782
CV (%)		0.96	3.74	1.74	1.10	1.84

Table H.3a Effects of phosphorus fertilizer rate and placement on seed protein concentration, by site in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Protein (g kg^{-1})				
-	0	347*a*	311	344	343	338
-	22.5	347*a*	312	-	343	340
-	45	359*a*	307	345	342	340
-	90	343*a*	307	347	343	338
-	0	347	311	344	343	338
Seed-Placed	-	351	311	-	343	341
Side-Band	-	349	306	345	343	339
Broadcast	-	349	308	345	343	339
-	0	347	311	344	343*ab*	338
Seed-Placed	22.5	348	312	-	347*a*	342
	45	351	311	343	342*ab*	344
	90	353	309	347	340*b*	337
Side Band	22.5	346	309	345	342*ab*	340
	45	349	304	346	341*ab*	338
	90	352	303	345	345*ab*	338
Broadcast	22.5	347	313	343	342*ab*	338
	45	348	305	345	343*ab*	339
	90	353	308	348	344*ab*	339
Mean		349	309	345	343	339
ANOVA		$P > F$				
Rate		0.0077	0.2687	0.2749	0.4920	0.1687
Placement		0.5869	0.3884	0.8448	0.9878	0.2931
Rate*Placement		0.9585	0.9408	0.4173	0.0053	0.2280
CV (%)		1.60	2.93	1.58	1.33	1.22

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table H.3b Effects of phosphorus fertilizer rate and placement on seed protein concentration, by site in 2015.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Protein (g kg^{-1})				
-	0	354	352	349*a*	348	348
-	22.5	355	352	348*a*	349	347
-	45	355	350	348*a*	352	351
-	90	355	353	343*a*	348	349
-	0	354	352	349*a*	348	348
Seed-Placed	-	355	351	342*a*	351	350
Side-Band	-	355	352	348*a*	-	-
Broadcast	-	355	352	348*a*	349	348
-	0	354	352	349	348	348
Seed-Placed	22.5	355	353	346	354	347
	45	355	348	346	351	354
	90	355	352	335	347	349
Side Band	22.5	354	351	349	-	-
	45	354	352	349	-	-
	90	358	355	346	-	-
Broadcast	22.5	355	351	349	344	348
	45	355	352	349	352	348
	90	354	352	348	350	349
Mean		355	352	347	350	349
ANOVA		$P > F$				
Rate		0.6699	0.1827	0.0115	0.6761	0.0995
Placement		0.7545	0.3801	0.0051	0.5874	0.2293
Rate*Placement		0.1905	0.2407	0.1113	0.2500	0.1813
CV (%)		0.72	1.37	1.74	2.16	1.32

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Appendix I

I. Seed Oil Concentration (Chapter 2)

Table I.1a Effects of phosphorus fertilizer rate and placement on seed oil concentration, by site in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013				
		Oil (g kg^{-1})				
-	0	144*ab*	187*a*	162	147	163
-	22.5	145*a*	188*a*	164	149	167
-	45	143*ab*	189*a*	164	151	167
-	90	142*b*	182*a*	174	148	164
-	0	144	187*ab*	162	147	163
Seed-Placed	-	142	184*b*	162	149	166
Side-Band	-	144	188*a*	164	149	166
Broadcast	-	144	186*ab*	175	150	166
-	0	144	187	162	147	163
Seed-Placed	22.5	143	186	163	149	166
	45	142	187	163	152	168
	90	141	180	160	147	164
Side Band	22.5	146	187	164	147	167
	45	143	191	164	149	167
	90	143	184	164	149	164
Broadcast	22.5	145	190	165	150	167
	45	145	189	164	153	167
	90	142	181	200	148	164
Mean		144	186	167	149	166
ANOVA		*P* > *F*				
Rate		0.0307	0.0427	0.4066	0.2527	0.2137
Placement		0.0606	0.0259	0.2441	0.6517	0.8785
Rate*Placement		0.2929	0.3221	0.2920	0.7126	0.8806
CV (%)		1.68	2.72	17.50	2.74	1.92

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table I.1b Effects of phosphorus fertilizer rate and placement on seed oil concentration, by site in 2013.

Treatment		Roblin	Portage	St Adolphe
Placement	Rate (kg P_2O_5.ha^{-1})	2013		
		Oil (g kg^{-1})		
-	0	149	161	167
-	22.5	148	159	167
-	45	151	157	169
-	90	-	-	-
-	0	149	161	167
Seed-Placed	-	150	158	169
Side-Band	-	-	-	-
Broadcast	-	149	158	168
-	0	149	161	167
Seed-Placed	22.5	148	158	168
	45	151	158	170
Broadcast	22.5	148	160	167
	45	150	156	169
Mean		150	160	170
ANOVA		*P > F*		
Rate		0.2009	0.2779	0.0769
Placement		0.9709	0.9700	0.3337
Rate*Placement		0.7640	0.2656	0.9216
CV (%)		2.47	3.05	1.67

Table I.2a Effects of phosphorus fertilizer rate and placement on seed oil concentration, by site in 2014.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014				
		Oil ($g\ kg^{-1}$)				
-	0	142	166	164	153	163
-	22.5	144	167	165	156	162
-	45	145	166	164	156	161
-	90	145	167	164	156	162
-	0	142	166	164	153*b*	163
Seed-Placed	-	145	165	163	154*ab*	161
Side-Band	-	144	167	165	157*a*	162
Broadcast	-	144	167	164	157*ab*	161
-	0	142	166	164	153	163*a*
Seed-Placed	22.5	144	166	163	154	162*a*
	45	145	165	164	154	160*a*
	90	145	165	163	154	162*a*
Side Band	22.5	144	167	166	156	159*a*
	45	144	167	165	157	163*a*
	90	146	166	163	157	164*a*
Broadcast	22.5	144	167	165	158	164*a*
	45	145	164	163	155	160*a*
	90	144	170	165	156	161*a*
Mean		144	166	164	156	162
ANOVA		$P > F$				
Rate		0.6711	0.5429	0.3212	0.8603	0.3648
Placement		0.8021	0.2810	0.1143	0.0420	0.5483
Rate*Placement		0.9016	0.0923	0.2140	0.7690	0.0149
CV (%)		1.79	1.69	1.28	1.94	1.71

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Table I.2b Effects of phosphorus fertilizer rate and placement on seed oil concentration, by site in 2014.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5.ha^{-1})	2014				
		Oil (g kg^{-1})				
-	0	178	174	148	164	162
-	22.5	176	175	146	166	161
-	45	176	176	145	164	163
-	90	176	175	146	164	166
-	0	178	174	148	164	162
Seed-Placed	-	177	174	147	164	163
Side-Band	-	175	175	-	-	-
Broadcast	-	175	176	145	164	163
-	0	178	174	148	164	162
Seed-Placed	22.5	178	176	147	167	160
	45	176	173	146	164	163
	90	177	173	147	161	165
Side Band	22.5	174	174	-	-	-
	45	176	176	-	-	-
	90	175	175	-	-	-
Broadcast	22.5	175	176	145	164	162
	45	176	177	144	164	162
	90	175	176	146	166	166
Mean		176	175	146	165	16.3
ANOVA		*P > F*				
Rate		0.9832	0.9018	0.6782	0.4761	0.0564
Placement		0.1395	0.3512	0.1516	0.6006	0.6557
Rate*Placement		0.6440	0.6579	0.8570	0.1411	0.7988
CV (%)		1.41	2.30	2.41	1.95	2.09

Table I.3a Effects of phosphorus fertilizer rate and placement on seed oil concentration, by site in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		Oil (g kg^{-1})				
-	0	164	189	176	172	184
-	22.5	165	190	-	174	182
-	45	165	190	176	174	183
-	90	163	191	175	173	183
-	0	164	189	176	172	184
Seed-Placed	-	164	190	-	173	183
Side-Band	-	164	191	176	174	183
Broadcast	-	165	190	176	173	183
-	0	164	189	176	172	184
Seed-Placed	22.5	166	188	-	173	181
	45	164	190	177	173	184
	90	162	192	174	172	184
Side Band	22.5	165	191	177	174	183
	45	164	190	175	175	183
	90	162	191	176	173	183
Broadcast	22.5	163	190	176	174	183
	45	166	190	176	173	184
	90	165	190	176	173	183
Mean		164	190	176	173	183
ANOVA		*P > F*				
Rate		0.3236	0.6598	0.6076	0.6588	0.1536
Placement		0.7922	0.6984	0.9066	0.2673	0.5026
Rate*Placement		0.3341	0.8363	0.5450	0.9578	0.1983
CV (%)		2.58	1.63	1.66	1.95	0.84

Table I.3b Effects of phosphorus fertilizer rate and placement on seed oil concentration, by site in 2015.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2015				
		Oil ($g\ kg^{-1}$)				
-	0	173	175	153	177	176*ab*
-	22.5	172	175	152	176	176*a*
-	45	172	175	154	176	173*b*
-	90	173	174	154	176	175*ab*
-	0	173	175	153	177	176
Seed-Placed	-	172	175	153	176	174
Side-Band	-	172	174	153	-	-
Broadcast	-	172	175	153	177	175
-	0	173	175	153	177	176
Seed-Placed	22.5	172	175	152	174	176
	45	172	175	153	176	171
	90	172	174	155	177	175
Side Band	22.5	172	175	153	-	-
	45	173	175	152	-	-
	90	173	172	152	-	-
Broadcast	22.5	173	175	151	179	177
	45	172	175	155	176	174
	90	172	175	153	175	175
Mean		172	175	153	176	175
ANOVA		*P > F*				
Rate		0.8957	0.0674	0.2648	0.9599	0.0177
Placement		0.9190	0.2273	0.7236	0.4228	0.1694
Rate*Placement		0.8866	0.2992	0.1847	0.1245	0.5420
CV (%)		0.93	1.52	1.66	1.76	2.04

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Appendix J

J. 1000 Seeds Weight (Chapter 2)

Table J.1a Soybean seed size as affected by phosphorus fertilizer rate and placement, by site in 2013.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2013				
		1000 seed weight (g)				
-	0	160.7	167.1	166.7	172.4	185.0
Seed-Placed	22.5	172.5	163.4	177.3	174.0	192.6
	45	164.5	145.4	167.3	172.9	182.4
	90	163.9	158.0	169.4	180.1	194.5
Side Band	22.5	163.4	156.6	168.2	172.6	189.8
	45	165.8	139.2	177.2	173.2	189.3
	90	166.0	157.6	168.8	173.9	185.6
Broadcast	22.5	161.6	155.6	167.2	173.1	189.8
	45	163.6	143.9	166.8	179.7	185.1
	90	165.9	159.3	170.5	178.2	184.7
Mean		164.8	154.6	169.9	175.0	187.9
ANOVA		*P > F*				
Rate		0.9415	0.0749	0.9581	0.0929	0.5281
Placement		0.6256	0.6945	0.5990	0.1328	0.3042
Rate*Placement		0.5038	0.9469	0.2618	0.2487	0.0649
CV (%)		5.1	9.78	5.87	2.84	3.38

Table J.1b Soybean seed size as affected by phosphorus fertilizer rate and placement, by site in 2013.

Placement	Rate (kg P_2O_5 ha^{-1})	Roblin	Portage	St. Adolphe
		2013		
		1000 seed weight (g)		
-	0	181.6	160.3	163.9
Seed-Placed	22.5	189.0	181.6	165.2
	45	196.7	171.8	172.4
Broadcast	22.5	178.6	159.6	168.6
	45	174.1	157.1	163.1
Mean		184.0	166.1	166.6
ANOVA		*P > F*		
Rate		0.8571	0.3153	0.8364
Placement		0.0245	0.0073	0.461
Rate*Placement		0.3381	0.5678	0.1258
CV (%)		8.34	10.42	0.35

Table J.2a Soybean seed size as affected by phosphorus fertilizer rate and placement, by site in 2014.

Placement	Rate (kg P_2O_5 ha^{-1})	Brandon	Arborg	Beausejour	Carberry	Melita
		2014				
		1000 seed weight (g)				
-	0	166.7	176.2	166.9	142.8	174.6
Seed-Placed	22.5	170.4	178.0	167.5	143.0	172.1
	45	173.5	182.3	169.4	139.1	169.6
	90	179.0	173.3	167.9	137.3	170.8
Side Band	22.5	173.8	173.2	168.4	147.6	167.3
	45	173.3	173.1	170.0	149.4	172.8
	90	178.3	170.6	170.7	145.8	172.8
Broadcast	22.5	171.7	175.7	167.5	145.5	174.5
	45	173.8	173.6	167.8	147.0	172.1
	90	174.2	175.3	170.7	146.4	175.6
Mean		173.5	175.1	168.7	144.4	172.2
ANOVA		*P > F*				
Rate		0.0162	0.2100	0.1932	0.3188	0.4866
Placement		0.5603	0.0234	0.3873	<.0001	0.0899
Rate*Placement		0.5365	0.2832	0.5598	0.3975	0.1998
CV (%)		2.93	3.25	1.59	3.49	2.53

Table J.2b Soybean seed size as affected by phosphorus fertilizer rate and placement, by site in 2014.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate ($kg\ P_2O_5\ ha^{-1}$)	2014				
		1000 seed weight (g)				
-	0	178.6	165.5	144.0	176.1	161.7
Seed-Placed	22.5	178.5	157.2	148.8	172.8	166.4
	45	181.6	159.9	149.0	175.2	165.8
	90	178.2	160.6	148.6	172.2	163.1
Side Band	22.5	178.2	159.4	-	-	-
	45	178.2	153.8	-	-	-
	90	178.8	163.9	-	-	-
Broadcast	22.5	178.9	157.0	146.7	179.8	164.3
	45	178.1	156.7	146.1	177.2	164.3
	90	175.4	157.2	144.0	175.7	163.4
Mean		178.5	159.1	146.7	175.6	164.1
ANOVA		*P > F*				
Rate		0.5358	0.5886	0.6023	0.7271	0.6796
Placement		0.4968	0.8052	0.0251	0.1489	0.5749
Rate*Placement		0.6829	0.7896	0.7312	0.7478	0.8854
CV (%)		2.26	6.89	3.23	3.63	3.02

Table J.3a Soybean seed size as affected by phosphorus fertilizer rate and placement, by site in 2015.

Treatment		Brandon	Arborg	Beausejour	Carberry	Melita
Placement	Rate (kg P_2O_5 ha^{-1})	2015 1000 seed weight (g)				
-	0	158.1	170.6	173.1	160.8	170.1
Seed-Placed	22.5	160.3	179.0	-	155.9	168.7
	45	158.4	174.7	169.0	159.3	171.6
	90	159.8	170.3	173.0	156.7	172.7
Side Band	22.5	158.9	174.7	174.0	160.5	173.9
	45	159.2	170.2	172.6	160.2	170.5
	90	161.5	170.9	171.3	162.8	173.3
Broadcast	22.5	157.6	169.7	171.5	160.1	169.8
	45	159.2	169.9	173.2	157.4	175.0
	90	159.4	170.0	175.0	161.5	171.6
Mean		159.2	172.0	172.5	159.5	171.7
ANOVA		*P > F*				
Rate		0.4760	0.0588	0.5206	0.3671	0.4895
Placement		0.6345	0.0267	0.6897	0.0075	0.5788
Rate*Placement		0.7068	0.2561	0.2385	0.1306	0.2143
CV (%)		1.96	3.5	2.45	2.38	2.47

Table J.3b Soybean seed size as affected by phosphorus fertilizer rate and placement, by site in 2015.

Treatment		Carman	Roseisle	Roblin	Portage	St. Adolphe
Placement	Rate (kg P_2O_5 ha^{-1})	2015				
		1000 seed weight (g)				
-	0	169.3	166.0	148.0	196.2	167.0*ab*
Seed-Placed	22.5	168.7	170.3	144.8	195.0	162.1*b*
	45	170.4	175.8	146.2	195.0	174.6*a*
	90	165.3	172.6	142.7	191.4	166.9*ab*
Side Band	22.5	167.1	166.8	149.1	-	-
	45	170.4	173.6	143.9	-	-
	90	173.7	176.4	145.6	-	-
Broadcast	22.5	166.8	169.3	147.0	195.7	162.2*b*
	45	171.1	175.8	148.8	195.7	160.6*b*
	90	170.4	174.8	148.8	195.7	162.4*b*
Mean		169.3	172.1	146.5	195.0	165.1
ANOVA		*P > F*				
Rate		0.143	0.0044	0.8025	0.7874	0.1168
Placement		0.3721	0.8505	0.1658	0.4338	0.0054
Rate*Placement		0.1265	0.6046	0.4378	0.7894	0.0267
CV (%)		2.57	5.9	3.31	2.82	3.83

Means followed by the same letter grouping are not significantly different at $P < 0.05$.

Appendix K

K. Regression Graphs (Chapter 2)

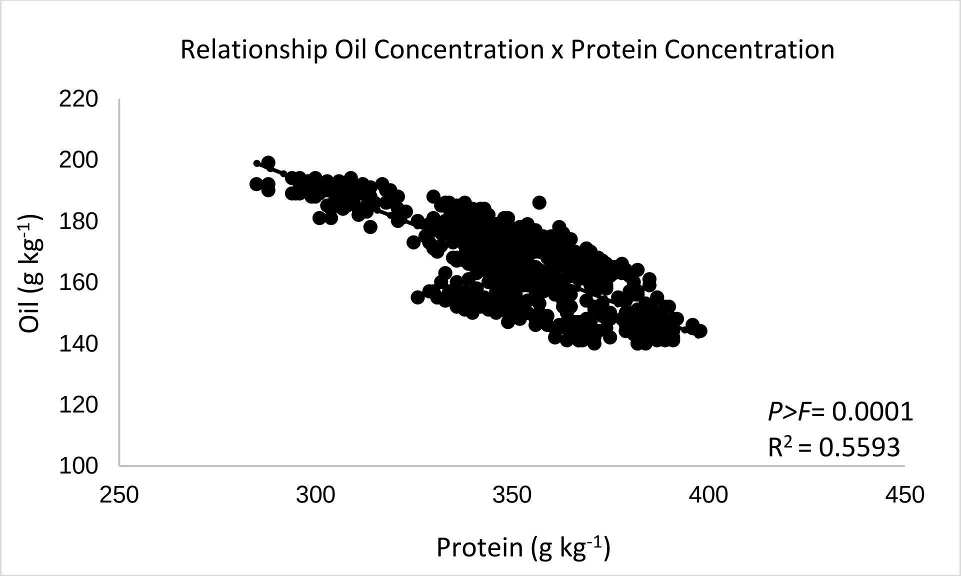

Figure K.1 Relationship between seed oil and seed protein concentration for sites established in 2013, 2014 and 2015.

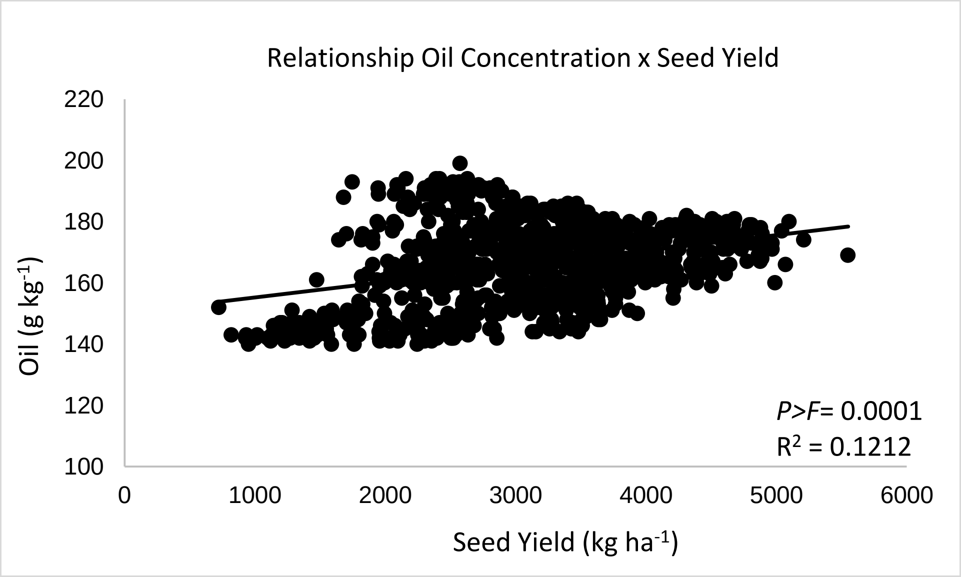

Figure K.2 Relationship between seed oil and seed protein concentration for sites established in 2013, 2014 and 2015.

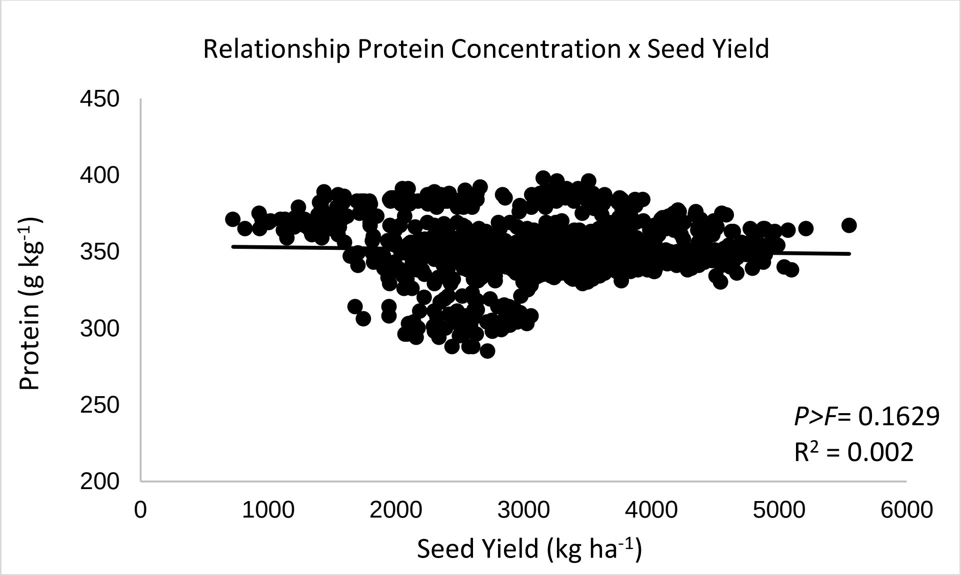

Figure K.3 Relationship between seed protein concentration and seed yield for sites established in 2013, 2014 and 2015.

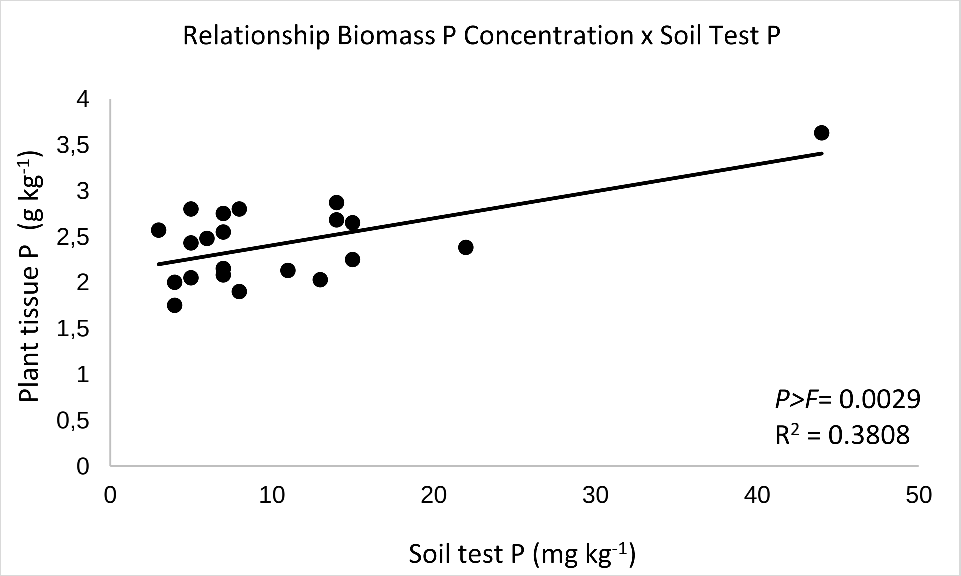

Figure K.4 Relationship between plant tissue P concentration and soil test P concentration, at R3 growth stage.

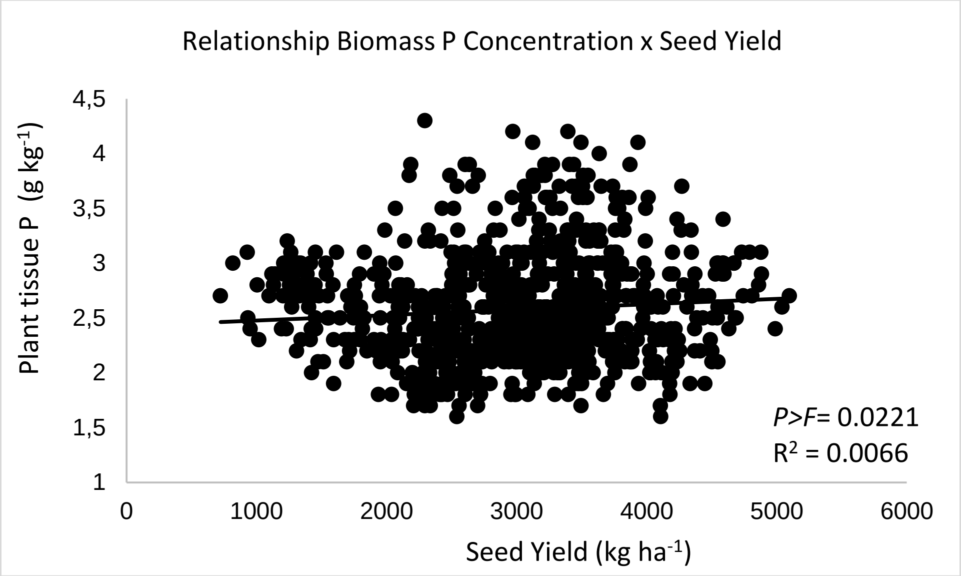

Figure K.5 Relationship between plant tissue P concentration and soil test P concentration for sites established in 2013, 2014 and 2015.

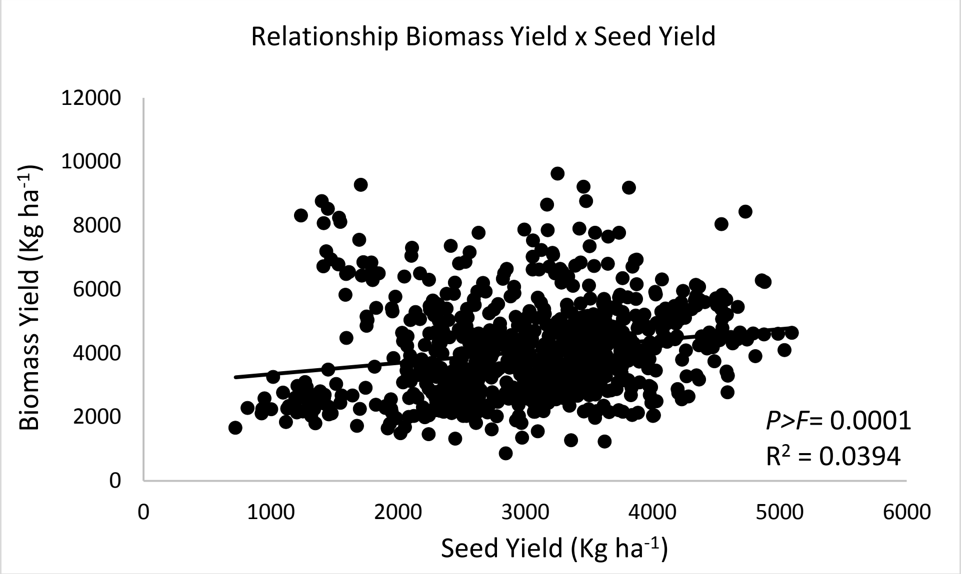

Figure K.6 Relationship between biomass dry matter (R3 growth stage) and seed yield for sites established in 2013, 2014 and 2015.

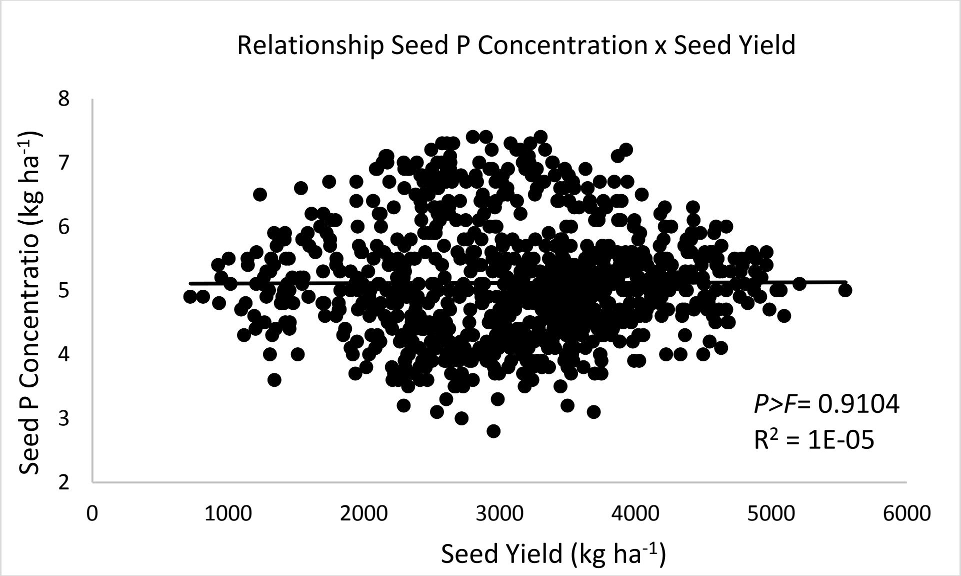

Figure K.7 Relationship between seed P concentration and seed yield, for sites established in 2013, 2014 and 2015.

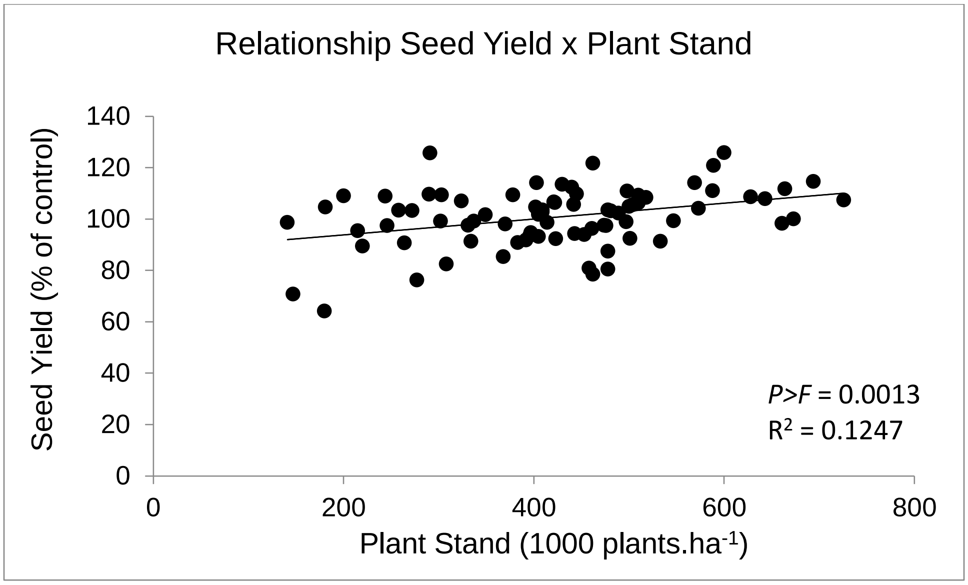

Figura K.8 Relationship between the percent of seed yield, which is the yield of the seed-placed fertilizer treatment divided by the control, and plant stand counts.

Appendix L

L. General Information (Chapter 3)

Table L.1 Legal land location and soil survey of long term sites used for the study described in chapter 3.

Site	Legal Land Location	Soil Series	Soil Classification[w]	Agricultural Capability[z]
Brandon	NE 27-10-19 W	Newdale + Varcoe + Drokan	OBC + GRBC + RHG	$3T^7 2W^2 5W^1$
Forrest	SW 21-12-18 W	Levine + Manson + Basker	GCR + CR + RHG	$3I^5 2I^3 5WI^2$
Carman	NW 23-6-5 W	Denham	OBC	1

[z] Superscript numbers mean the percentile of the map unit that contains the limitation from a total of 10. The letters I, T and W stand for the agricultural limitations, which are soil inundation (by a water stream), topography and excess water, respectively.

[w] Orthic Black Chernozem (OBC), Gleyed Rego Black Chernozem (GRBC), Rego Humic Gleysol (RHG), Gleyed Cumulic Regosol (GCR), Cumulic Regosol (CR).

Data obtained through the Manitoba Food and Rural Development.

Table L.2a Means of soil test results for fall soil sampling in 2013.

Treatment		pH	NO_3^- - N	P	K	Ca	Mg
Historical annual P (kg ha^{-1})^y	Fertilizer Cd concentration			mg kg^{-1}			
				Brandon 2013			
0	-	7.8	2.8	10.8	455.5	5417.1	779.2
20	Low	7.7	2.9	22.1	461.1	5478.7	816.7
	Medium	7.7	2.4	20.2	462.0	5437.9	820.3
	High	7.7	6.3	24.2	474.7	5473.5	847.3
40	Low	7.8	2.7	32.1	459.6	5390.8	788.4
	Medium	7.7	3.3	35.5	437.9	5185.3	894.8
	High	7.8	2.9	32.6	456.4	5550.4	882.2
80	Low	7.8	2.9	49.8	468.0	5270.6	785.6
	Medium	7.6	3.2	54.5	461.7	5278.7	844.3
	High	7.7	3.3	57.2	494.2	5362.8	818.5
				Carman 2013			
0	-	5.1	42.1	19.6	288.7	2171.3	376.2
20	Low	5.2	40.9	32.2	274.3	2247.9	418.3
	Medium	5.2	36.5	27.9	274.5	2250.8	414.8
	High	5.2	43.2	32.6	278.8	2191.1	406.9
40	Low	5.1	41.5	51.3	285.6	2133.2	377.0
	Medium	5.1	47.7	52.4	278.7	2165.2	391.9
	High	5.2	45.1	54.2	280.2	2178.8	386.9
80	Low	5.1	44.7	90.2	282.7	2240.2	414.6
	Medium	5.1	43.0	90.6	275.3	2105.3	391.6
	High	5.1	45.7	93.1	281.3	2162.5	400.9
				Forrest 2013			
0	-	7.7	3.3	6.8	207.1	5178.1	616.9
20	Low	7.7	2.7	14.0	196.5	5112.4	656.4
	Medium	7.6	3.4	15.2	215.8	5153.5	663.9
	High	7.7	4.0	15.3	207.5	5343.4	640.7
40	Low	7.7	3.3	22.4	206.2	5295.6	657.0
	Medium	7.7	3.2	22.3	200.9	4851.3	687.2
	High	7.6	4.3	22.4	201.3	4891.8	693.9
80	Low	7.6	3.9	34.2	193.4	5085.8	616.9
	Medium	7.7	3.6	45.1	199.5	5154.9	692.4
	High	7.7	2.9	41.1	199.5	5342.1	701.7

Table L.2b Means of soil test results for fall soil sampling in 2013.

Treatment		Cu	Fe	Mn	Zn	Cd	Conductance
Historical annual P (kg ha^{-1})^{y}	Fertilizer Cd concentration	mg kg^{-1}				μg kg^{-1}	μs cm^{-1}
				Brandon 2013			
0	-	2.2	20.7	17.3	0.8	109.5	361.4
20	Low	2.3	21.2	15.9	0.9	116.9	371.4
	Medium	2.0	20.2	14.9	0.9	119.3	363.5
	High	2.1	21.1	15.7	1.1	141.7	394.8
40	Low	2.3	21.0	16.4	0.9	114.8	338.5
	Medium	2.2	23.9	16.0	1.0	124.4	378.6
	High	2.1	19.2	13.0	1.1	150.8	357.7
80	Low	2.2	20.6	13.9	1.0	115.9	336.4
	Medium	2.0	24.9	16.9	1.2	139.2	374.8
	High	2.5	22.9	16.7	1.7	212.2	343.6
				Carman 2013			
0	-	1.4	205.7	40.6	2.5	186.8	290.6
20	Low	1.2	191.9	40.4	2.4	188.9	296.3
	Medium	1.2	191.9	39.1	2.4	193.3	263.1
	High	1.3	196.6	39.4	2.6	213.6	300.6
40	Low	1.3	224.4	40.6	2.4	188.8	292.3
	Medium	1.2	215.8	39.4	2.7	212.0	324.8
	High	1.3	212.7	38.1	3.0	251.1	313.0
80	Low	1.4	208.3	43.4	2.7	195.9	319.3
	Medium	1.4	218.6	40.8	2.9	233.0	304.6
	High	1.2	208.1	39.3	3.5	336.3	334.0
				Forrest 2013			
0	-	1.0	16.2	13.4	0.6	120.9	320.5
20	Low	1.0	16.9	12.6	0.6	121.3	329.5
	Medium	1.1	17.3	13.9	0.8	128.0	332.8
	High	1.2	16.6	13.7	0.9	148.4	343.7
40	Low	1.0	16.8	12.4	0.7	123.4	333.8
	Medium	1.0	17.3	13.5	0.9	139.1	309.3
	High	1.0	17.7	13.6	1.0	158.5	313.6
80	Low	1.1	17.2	12.4	0.7	111.4	324.6
	Medium	1.0	18.0	13.6	1.0	158.5	313.6
	High	1.1	17.2	12.0	1.4	199.5	339.9