Effect of Seed-Placed Phosphorus and Sulphur Fertilizers on Canola Plant Stand, Early Season Biomass and Seed Yield

by

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ABSTRACT

Seed-placed phosphorus (P) and sulphur (S) fertilizers can reduce canola plant stands. Field studies were conducted to determine the effect of various sources and rates of seed-placed P and S fertilizers on canola plant stand, early season biomass accumulation and seed yield. Conventional granular P and S blends increased the risk of seedling damage, but increased the frequency of yield response. Liquid fertilizers were similar in seedling damage but generally less effective in increasing seed yield compared to granular fertilizers. Novel fertilizers were more seed-safe but less reliable than conventional sources in increasing seed yield. A growth room experiment was conducted to determine the effect of soils from different landscape positions on the toxicity of seed-placed ammonium sulphate (AS) and monoammonium phosphate (MAP). Canola emergence was reduced and delayed by seed-placed MAP and AS. Ammonium sulphate in particular has a high risk of NH_3 toxicity on calcareous hilltop soils.

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FOREWORD

This thesis has been prepared using the guidelines established by the Department of Soil Science at the University of Manitoba. Chapter 1 includes a brief introduction to the relevant literature and a list of objectives for the overall study; a more detailed review of the literature is provided in Appendix A. Chapter 2 contains a manuscript for the phosphorus and sulphur fertilization field study led by Dr. Cynthia Grant, the lead researcher of this project. This study was conducted across Canada and included collaborators in Lethbridge, AB (Dr. Brian Beres), Thunder Bay, ON (Dr. Tarlok Sahota) and Normandin, QE (Dr. Denis Pageau) and Brandon (Dr. Cynthia Grant). I was responsible for managing both the Carman and Kelburn, MB research sites in 2011 and 2012, as well as the statistical analysis of the field data collected (plant stand, biomass and seed yield data from all site years). Soil nutrient, plant nutrient uptake and oil quality data were also collected and will eventually be added to this manuscript. Funding for this field study came from the Canola Council of Canada and Agriculture and Agri-Food Canada. I would like to acknowledge the support of our contributors, Dr. Cynthia Grant, Dr. Don Flaten, John Heard, Dr. Brian Beres, Dr. Tarlok Sahota and Dr. Denis Pageau with co-authorship. Chapter 3 contains a manuscript for a growth chamber study. I designed and conducted this experiment in 2012 with the guidance of Dr. Don Flaten. I will be the lead author for chapter 3, with Dr. Don Flaten and Dr. Cynthia Grant as co-authors. Chapters 2 and 3 from this thesis will be submitted to the Canadian Journal Soil

Science, and therefore the reference style of this journal has been used throughout the thesis. Chapter 4 provides a summary and synthesis for the overall study.

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1. INTRODUCTION

Canola is the major oilseed crop grown in Canada; however it is often grown on soil deficient in phosphorus (P) and/or sulphur (S) (Canola Council of Canada, 2011c). Canola requires relatively large amounts of P and S to reach yield potential compared to cereal crops (Grant and Bailey 1993); to achieve a canola seed yield of 2520 kg ha^{-1}, the crop will require approximately 67-84 kg P_2O_5 ha^{-1} and 30-31 kg S ha^{-1} (CFI 2001).

Plants take up S in the form of SO_4^{2-}-S, which moves to the root by mass flow. Sulphate can be supplied to the root by soil solution and adsorbed SO_4^{2-}, and soluble SO_4^{2-}-S released from fertilizer (Havlin et al. 2005). Adequate S supplies are especially important during flowering and seed set to reach optimal seed yield and quality (Malhi and Gill 2002). Supplying an available source of S at the time of seeding reduces the risk of S deficiency later in the growing season (Malhi et al. 2005). On S-deficient soils, applying S fertilizer at a rate of 15-30 kg S ha^{-1} is sufficient to reach optimal seed yields (Grant et al. 2012).

Sulphur fertilizers differ in their ability to supply plant available SO_4^{2-} in the year of application. Ammonium sulphate (AS) is commonly used in canola crop production because it provides plants with an immediate, reliable source of SO_4^{2-} (Grant et al. 2012). Although thiosulphate requires microbial oxidation to be converted to SO_4^{2-}, ammonium thiosulphate (ATS) is considered to be equally effective in supplying sulphate in the year of application for canola. Oxidation is temperature dependent; although temperatures are generally conducive to adequate rates of sulphate release, cool temperatures at the time of seeding may slow the conversion to sulphate (Goos and Johnson 2001a). Similarly, elemental S (ES) also requires microbial oxidation to be converted to SO_4^{2-}; however, conversion does not generally occur at a rate sufficient to meet crop demand in the year of application, especially in cool and dry growing conditions (Franzen and Grant 2008). MicroEssentials S15 (MES15) is a novel fertilizer that is formulated with 50% AS and 50% ES, which could provide both immediate and slow-release SO_4^{2-}. However, banding ES creates a hydrophobic band, which restricts microbial oxidation (Janzen and Bettany 1986); therefore oxidation of ES in MES15 is negligible in the year of application (Kroeker 2005). Decreasing particle size can improve rates of oxidation (Janzen and Bettany 1986), and therefore Vitasul, another ES product, is formulated to disperse quickly in soil as fine particles.

Unlike S which moves to the root by mass flow, P is mainly taken up by diffusion in the orthophosphate form (Kovar and Claassen 2005). Phosphorus deficiency early in the growing season can lead to irreversible reductions in growth and development, and hence it is a common practice to supply available P early in the growing season as fertilizer placed near or with the seed (Grant et al. 2001). This "starter P" will often result in increased growth and P uptake, especially on soils with low soil test P or cold or wet soils where diffusion of P and root growth are limited (Havlin et al. 2005).

Monoammonium phosphate is the most commonly used P fertilizer in Canada. Phosphorus use efficiency is low, however, generally only being ~20% in the year of application (Chien et al. 2011). Canola is relatively efficient at utilizing fertilizer P because its roots can proliferate in the fertilizer band (Strong and Soper 1974) and it can acidify the rhizosphere to solubilise Ca-P precipitates (Grant et al. 2001, Trolove et al. 2003). To improve P uptake polymer coatings on MAP were designed to minimize the fertilizer-soil contact, thus increasing fertilizer use efficiency by reducing P precipitation and releasing soluble P to match crop requirement throughout the growing season. Phosphorus is released by diffusion, so the release rate is mediated by coating thickness and temperature. In comparison to uncoated MAP, coated MAP has been show to increase P uptake by barley (Leytem and Westermann 2005), but not by canola (Qian et al. 2005). The lack of difference in P uptake between the coated and uncoated MAP for canola may be due to canola's ability to solubilise Ca-P precipitates.

Ammonium polyphosphate is generally considered to be as effective as MAP in supplying available P in most crops in most soils (Chien et al. 2011). Polyphosphate chains require hydrolysis to be converted to the orthophosphate form, but this generally occurs rapidly in soil (Hedley and McLaughlin 2005). Liquid formulations have been found to more effective than granular forms in increasing P uptake in extremely dry and calcareous soils (Holloway et al. 2001). Also, polyphosphates have greater mobility than orthophosphates in alkaline/calcareous soils (Hedley and McLaughlin 2005) which could increase the fertilizer reaction zone. Larger fertilizer reaction zones should increase root absorption of P (Havlin 2005) by allowing the roots to intercept the patch of P-rich soil more easily and also enhance root proliferation in that zone (Beever 1987).

Placing P and S fertilizers in the seed-row is both efficient and convenient, especially as farmers are adopting one pass seeding systems, putting down all of their fertilizer at the time of seeding. However, farmers are also adopting low disturbance, low seed bed utilization seeding equipment, which decreases the amount of fertilizer that can be safely placed with the seed. Only 22 kg P_2O_5 ha^{-1} as MAP or 11 kg S ha^{-1} as AS is recommended to be placed with the seed (MAFRI 2007); although, as previously mentioned, canola crop requirements are much higher. In addition, there are no set of recommended safe rates for seed-placed P and S blends. Canola is relatively sensitive to seed placed fertilizers compared to cereals (Nyborg 1961). Applying P and S fertilizers above the recommended rate can cause significant seedling damage that can reduce yield potential (Grant et al. 2004). Also, sub-lethal osmotic and ammonia (NH_3) toxicity from fertilizers can delay the emergence of canola (Dowling 1998).

Since fertilizers differ in toxicity, selecting an appropriate source is important to minimize seedling damage. Seedling damage increases with increasing salt index, as this increases the effect on osmotic potential of the soil solution. The relative salt index of P fertilizers is generally less than for S fertilizers. For example, the salt indexes for MAP and APP are 26.7 and 20.0, respectively, while the salt indexes for AS and ATS are 88.3 and 90.4, respectively (Havlin et al. 2005). Increasing seedbed utilization (SBU) and soil moisture at the time of seeding will dilute fertilizer salts and decrease osmotic stress on seedlings (Nyborg and Hennig 1959).

In addition, to osmotic stress, there is some risk of NH_3 toxicity for P and S fertilizers formulated with nitrogen. Monoammonium phosphate is considered to have relatively low NH_3 toxicity because the saturated solution of MAP has a pH of 3.5 (Hedley and McLaughlin 2005) and nitrification of NH_4^+ lowers the pH of the fertilizer band (Doyle and Cowell 1993) both of which favour NH_4^+ over NH_3. Because there is a higher N analysis in AS compared to MAP, the NH_3 toxicity risk is considered higher. Therefore, AS is considered to be as toxic as urea-ammonium-nitrate and urea (MAFRI 2007). Elemental S fertilizers are less toxic than AS or ATS because ES does not contain N, so there is no risk of NH_3 toxicity and ES contains no soluble salts and oxidizes slowly in soil and therefore has a much lower salt index than SO_4^{2-} (Grant et al. 2004).

In addition to fertilizer source, soil properties such as soil pH, CEC, texture, temperature and water content will also affect rate and amount of NH_3 formation (Fenn and Kissel 1973). Calcareous soils increase the risk of NH_3 toxicity of AS. Ammonium sulphate reacts with the $CaCO_3$ in the soil, forming ammonium carbonate ($(NH_4)_2CO_3$) and calcium sulphate ($CaSO_4$) (Eq. 1). The $CaSO_4$ precipitates, which drives the reaction to the right. The $(NH_4)_2CO_3$ spontaneously decomposes, releasing ammonia and carbon dioxide (Eq. 2), decreasing the pH of the surrounding soil (Eq. 3) (Fenn and Kissel 1973).

$$(NH_4)_2SO_4 + CaCO_3 \leftrightarrow (NH_4)_2CO_3 + CaSO_4 \quad (1)$$

$$(NH_4)_2CO_3 + H_2O \leftrightarrow 2NH_3\uparrow + H_2O + CO_2\uparrow \leftrightarrow 2NH_4OH \quad (2)$$

$$NH_4^+ + OH^- \leftrightarrow NH_4OH \leftrightarrow NH_3\uparrow + H_2O \quad (3)$$

Although seed-placed P and S fertilizers can reduce plant stands of canola, the optimum plant stand for canola is wide (40-200 plants m^{-2}) (Canola Council of Canada 2011b). At lower plant densities, canola can compensate by increasing the number of branches, pods and seed weight (Krogman and Hobbs 1975) and therefore lower plant densities do not consistently reduce seed yield (Grant et al. 2010, Johnson et al. 2001, 2002). However, reduced stand density can delay maturity (Harker et al. 2012), reduce oil quality (Grant et al. 2003a) and increase weed competition (Johnson et al. 2001). It is important to apply the appropriate source and rate of P and/or S fertilizer in the seed row to supply adequate available nutrients while minimizing seedling damage.

Given the importance of canola as a major oilseed crop in Canada, refining the guidelines for seed-placed P and S fertilizer with canola requires further attention. Currently there are no recommended safe rates for P and S blends in the seed-row with canola. Maximum recommended safe rates also need to be evaluated to determine if they are potentially yield limiting. In addition, novel fertilizers could differ in seedling toxicity and nutrient availability, and therefore need to be compared to conventional sources commonly used. Soil properties can also affect seedling toxicity of fertilizers; therefore, it is important to understand how emergence will be affected by seed-placed P and S in a field with variable soil properties.

A field experiment was conducted to determine the safe rates of various sources of seed-placed P and S fertilizers applied alone and as a blend in canola across wide range of soils and climatic conditions. Early season biomass and seed yield were also collected from the field study to determine if the recommended safe rates of fertilizers are yield limiting. In addition, novel fertilizers were compared to conventional sources in terms of seedling damage and nutrient availability. Since soil properties within a field can also affect fertilizer toxicity, a study was also conducted under controlled environment conditions to determine if soils from different landscape positions affected the toxicity of AS and MAP fertilizers placed in the seed-row with canola.

2. PLANT STAND, EARLY SEASON BIOMASS ACCUMULATION AND SEED YIELD OF CANOLA AS AFFECTED BY SOURCE AND RATE OF SEED-PLACED PHOSPHORUS AND SULPHUR FERTILIZER

Keywords: Canola (*Brassica napus*), phosphorus, sulphur, plant stand, early season biomass accumulation, seed yield

2.1 Abstract

Many farmers are adopting one-pass seeding systems, placing all their phosphorus (P) and sulphur (S) in the seed-row with canola; however, there are no recommended safe rates for seed-placed P and S fertilizer blends. Novel fertilizers such as coated monoammonium phosphate (cMAP), MicroEssentials S15 (MES15) and Vitasul may differ in terms of seed-safety and nutrient availability compared to conventional sources. Field studies at six locations across Canada were conducted in 2010, 2011 and 2012 to determine the effect of various sources and rates of seed-placed P and S fertilizers on plant stand, early-season biomass accumulation and seed yield of canola. Applying monoammonium phosphate (MAP) above the recommended rate (20 kg P_2O_5 ha^{-1}) rarely reduced plant stands; however, application of cMAP never reduced plant stands. Increasing the rate of MAP or cMAP from 20 to 40 kg P_2O_5 ha^{-1} had often increased seed yield, indicating that the recommended safe rate for P may be yield limiting. Increasing the rate of ammonium sulphate (AS) from 9 to 18 kg S ha^{-1} applied alone or as a blend often reduced plant stands at some sites and did not consistently increase seed yields. Liquid fertilizers were similar in seedling toxicity but were generally less effective in

increasing seed yield compared to granular fertilizers. MicroEssentials S15 and Vitasul often reduced seedling damage compared to conventional blends. The yield response to equivalent rates of MES15 and MAP/AS were generally similar; however, increasing from the low to high rate of MES15 resulted in greater seed yield, while there was often no benefit from additional AS. The Vitasul/MAP blend had significantly higher seed yield compared to MAP applied alone at 1 of 16 site years, indicating that Vitasul appeared to oxidize in some situations; however, the Vitasul blend was never superior to high MAP/low AS blend. Restricting AS to 9 kg S ha^{-1} is the most reliable way to provide sufficient sulphate (SO_4^{2-}) while avoiding seedling damage when AS fertilizer is seed-placed.

2.2 Introduction

Canola is the major oilseed crop grown in Canada, and a large portion of the crop rotation. Canola requires a relatively large amount of P and S compared to cereal crops (Grant and Bailey 1993) and it is often planted on soils deficient in either or both these nutrients (Canola Council of Canada 2011c). Phosphorus and S fertilizers are commonly applied in the seed-row with canola as farmers are adopting one-pass seeding systems. Phosphorus fertilizer is known to be most efficient if placed in a band, near or with the seed, especially in cold or wet conditions when root growth and P diffusion are restricted (Grant et al. 2001). Banding increases P use efficiency by placing P in a favourable position for plant uptake as well as minimizing soil-fertilizer contact, reducing P precipitation and adsorption in soil (Havlin et al. 2005). Canola is also very efficient at utilizing fertilizer P in a band because it can proliferate its roots within the fertilizer band

(Strong and Soper 1974) as well as acidify its rhizosphere (Trolove et al. 2003). Monoammonium phosphate and ammonium polyphosphate (APP) are conventional sources P fertilizer most commonly used in Canadian canola cropping systems because they provide soluble, plant available or quickly available forms of P (HPO_4^{2-} and $H_2PO_4^-$). Since these fertilizers are ammoniated and acidic in nature (Chien et al. 2011), they remain relatively soluble in alkaline and calcareous soil that are typically found in western Canada.

Dual banded P and S fertilizer has also been found to increase P uptake by enhancing P solubility (Rennie and Soper 1958; Morden 1986; Goos and Johnson 2001b). On the Canadian Prairies the S sources most commonly used in canola cropping systems are AS, ammonium thiosulphate (ATS) or elemental S (ES), which vary in their ability to supply plant available SO_4^{2-} (Grant et al. 2012). On S-deficient soils, AS and ATS are considered to be equally effective in supplying an adequate supply of immediately or quickly plant available SO_4^{2-} for canola in the year of application (Grant et al. 2003b, 2004). However, ES requires microbial oxidation to be converted to SO_4^{2-} and oxidation generally does not occur at a rate rapid enough to supply adequate SO_4^{2-} in the year of application in Canada (Franzen and Grant 2008). Blended products, such as Mosaic's MES15 which contains 50% AS and 50% ES, could provide both an immediately available and slow release forms of SO_4^{2-} if used over a number of years (Kroeker 2005). Decreasing the particle size and increasing the particle distribution of ES can increase the SO_4^{2-}-S release rates (Janzen and Bettany 1986); therefore, fertilizers such as Sulvaris' Vitasul, designed to break down quickly in soil to increase surface area of the ES particles, could maximize microbial oxidation and improve SO_4^{2-}-S availability.

Applying adequate S at the time of seeding reduces the risk of S deficiency during seed set and pod filling and can optimize seed yield (Malhi and Gill 2002). Unlike P, however, SO_4^{2-}-S is mobile in the soil and has been found to be equally effective in increasing yield in a variety of placements (Grant et al. 2004). Although seed-placed P and S fertilizer is regarded as an efficient and convenient placement and timing strategy, canola is relatively sensitive to seed-placed fertilizer compared to cereals. Significant seedling damage can occur at rates applied to satisfy crop nutrient requirements (Nyborg 1961). A canola crop with a target yield of 2520 kg ha^{-1} will require 67-84 kg P_2O_5 ha^{-1} and 30-31 kg S ha^{-1} (Canadian Fertilizer Institute 2001); however, the recommended safe rates for seed-placement are approximately 22 kg P_2O_5 ha^{-1} as MAP and 11 kg S ha^{-1} as AS (MAFRI 2007). There is no set of recommended safe rates for seed placed blends of P and S fertilizers. Seedbed utilization will also affect the concentration of salts in the seed-row and thus wider row spacing or narrower opener widths will decrease the rates of fertilizer that can be safely applied (Nyborg and Hennig 1969). When canola is grown frequently in the crop rotation applying seed-placed fertilizer to maintain soil fertility or achieve yield potential on P or S deficient soils may be an issue due to seedling damage.

Fertilizer sources differ in their salt and ammonia (NH_3) toxicity. Monoammonium phosphate has a much lower salt index (29.9) than AS (69.0) (Radar et al. 1943), so the potential for crop injury is much greater for AS. The potential to form NH_3 is also different for these two fertilizers. In neutral to acidic soil, MAP and AS applied in a band will have similar potential to form NH_3 because their saturated solution pH's are acidic (MAP 4.7 and AS 4.5) (Dowling 1988); however, in calcareous soil AS can react with calcium carbonate ($CaCO_3$) to form NH_3 (Fenn and Kissel 1973).

Soil moisture will also affect the salt stress cause by seed-placed fertilizer. Decreasing the soil moisture content can cause seedling damage by increasing the concentrations of fertilizer salts and increasing the osmotic pressure of the soil solution (Olson and Dreier 1956; Nyborg and Hennig 1969). Water content of the soil will also affect NH_3 formation from AS in calcareous soils. As the water content decreases, the precipitation of calcium sulphate increases, increasing the formation of ammonium carbonate which subsequently spontaneously breaks down and forms NH_3 (Fenn and Kissel 1973). Other soil properties such as high soil $CaCO_3$ content or pH will also increase NH_3 formation (Fenn and Kissel 1971).

Novel fertilizers could be less toxic than conventional fertilizers and could improve canola seedling emergence, especially in dry soil conditions or low seed-bed utilization seeding systems. Vitasul and MES15 both contain ES, which contains no salts and oxidizes slowly in soil solution and, therefore, has a lower salt index than SO_4^{2-} fertilizers (Grant et al. 2004). Vitasul is 100% ES, so there is also no risk of NH_3 toxicity. Polymer coated MAP decreases the dissolution and diffusion of fertilizer salts and could be applied safely in the seed-row at much higher rates than conventional MAP (Qian et al. 2010).

Although the novel fertilizers could reduce seedling damage, they may not release adequate amounts of nutrient to satisfy crop demand throughout the growing season. Banding ES is not recommended because ES forms a hydrophobic band which restricts microbial oxidation (Janzen and Bettany 1986). Grant et al. (2004) found that seed-placed ES is not as effective as broadcast ES in increasing canola seed yield. Therefore, oxidation of Vitasul may not occur at a rate to supply sufficient amounts of SO_4^{2-} to the crop when banded. Similarly, with MES15, under both field and controlled environment conditions, Kroeker (2005) found that only the SO_4-S from the MES15 appeared to be available to the crop in the year of application and the ES was not oxidized at a sufficient rate to be utilized by the canola crop in any appreciable amount. Coated MAP may restrict plant growth early in the growing season if low rates are applied because available P from coated MAP may be insignificant on low P or high CEC soils where it is quickly adsorbed (Leytem and Westermann 2005).

It is important to balance appropriate rate and source of P and S to optimize plant stand and adequate nutrition to maximize seed yield. According to the Canola Council of Canada (2011b) the optimum plant stand for canola is from 40-200 plants m^{-2}. Therefore, seed yields may not decline when seed-row fertilizer reduces plant densities (Grant et al. 2010; Johnston et al. 2001, 2002) because at lower plant densities, plants can compensate by increasing number of pods per plant, seeds per pod and seed weight (Krogman and Hobbs 1975). However, lower plants stands can delay maturity (McGregor 1987; Grant et al. 2010; Johnston et al. 2001, 2002) increasing the risk of frost damage in short season areas and the crop may not be capable of utilizing the added fertilizer inputs (Brandt et al. 2007).

The objective of this study was to determine the safe rates of various sources of seed-placed P and S fertilizers applied alone and as a blend in canola. We also wanted to determine if the recommended safe rates are yield limiting and if novel fertilizers are as available as conventional fertilizers.

2.3 Materials and Methods

2.3.1 Experimental Design and Treatments

The study was conducted in 2010, 2011 and 2012 at six sites across Canada: Lethbridge, AB; Normandin, QE; Thunder Bay, ON; and Brandon, Carman and Glenlea, MB. The experiment had treatments arranged as a randomized complete block design with four replicates. The treatments consisted of various sources and rates of seed-placed P and S fertilizers. Rates of P applied were 0, 20 (Low) or 40 kg P_2O_5 ha^{-1} (High) and rates of S applied were 0, 9 (Low) or 18 kg S ha^{-1} (High). The low rates of both P and S were chosen to reflect the approximate recommended safe rate of seed-placed fertilizer for canola seeded in good to excellent moisture conditions (MAFRI 2007). The low and high rates were also chosen to reflect the same ratio of P and S in the MES15 to allow for agronomically significant comparisons between sources.

1) Control
2) Low AS
3) Low ATS
4) High AS
5) High ATS
6) Low MAP
7) Low APP
8) Low Coated MAP
9) Low MicroEssentials S15
10) Low MAP/Low AS
11) Low Coated MAP/Low AS
12) Low APP/Low ATS
14) Low Coated MAP/High AS
15) Low APP/High ATS
16) High MAP
17) High APP
18) High Coated MAP
19) High MAP/Low AS
20) High Coated MAP/Low AS
21) High APP/Low ATS
22) High MicroEssentials S15
23) High MAP/High AS
24) High Coated MAP/High AS
25) High APP/High ATS

13) Low MAP/High AS

26) High MAP/High Vitasul

Table 2.1 Planting, emergence and harvesting date and seeding equipment used at each site year

Site	Year	Planting Date	Emergence Date	Harvest Date	Opener Type	Row Spacing (cm)	SBU (%)
Brandon	2010	Jun. 3	Jun. 9	Sep. 27	Knife	20.3	12.3
	2011	Jul. 26	Aug. 2	-	Knife	20.3	12.3
	2012	Jun. 5	Jun. 15	Aug. 27	Knife	20.3	12.3
Carman	2010	Jun. 29	-	Oct. 2	Knife	20.3	12.3
	2011	Jun. 29	Jul. 4	Oct. 3	Disc	19.1	7.8
	2012	May 8	May 21	Aug. 14	Knife	20.3	12.3
Kelburn	2011	Jun. 6	Jun. 15	Sep. 6	Knife	20.3	12.3
	2012	May 9	May 22	Aug. 23	Knife	20.3	12.3
Lethbridge	2010	May 18	Jun. 7	Sep. 15	Knife	22.9	10.9
	2011	May 10	May 25	Sep. 8	Knife	22.9	10.9
	2012	May 14	May 30	Sep. 2	Knife	22.9	10.9
Normandin	2010	May 14	May 25	Sep. 7	Disc	18.0	8.3
	2011	Jun. 21	Jun. 28	Oct. 24	Disc	18.0	8.3
	2012	May 23	Jun. 7	Sep. 12	Disc	18.0	8.3
Thunder Bay	2010	Apr. 30	May 23	Aug. 14	Disc	15.2	9.9
	2011	May 27	Jun. 7	Aug. 30	Disc	15.2	9.9
	2012	May 11	May 22	Aug. 17	Disc	15.2	9.9

Due to equipment and time limitations, liquid fertilizer treatments (3, 5, 7, 12, 15, 17, 21, 25) were omitted from Carman in 2011, Normandin and Thunder Bay site years. The seeding equipment used at each site varied (Table 2.1) but the seed bed utilization at most sites was approximately 12%. Nitrogen (N) was applied as a 75:25 blend of ESN:Urea at a rate appropriate to optimize yield at each location. Nitrogen rate for each plot was balanced for the N in the P and/or S fertilizer treatment. Nitrogen was placed in the mid-row or side-band. Canola was direct seeded into stubble at a recommended rate of 150 seeds m^{-2} at a depth of 12-25 mm (Canola Council of Canada 2011b). The canola cultivar used was InVigor 5440 (InVigor 5030 at Normandin). Weeds were controlled prior to seeding as well as in-crop with the appropriate herbicide.

2.3.2 Site Characteristics

To determine the site characteristics, soil samples were taken in spring, before seeding at each site-year. Four soil cores were taken at two locations in each of the four replicates. Soil cores were divided into 0-15, 15-30 and 30-60 cm depths and corresponding depths were bulked into a composite for each location. Soil samples were analyzed for 0.5M sodium bicarbonate extractable P, 0.0001 M calcium chloride extractable S and pH by 1:2 soil to water ratio. Soil texture was estimated by hand.

Table 2.2 Soil characteristics and cumulative rainfall two weeks after planting at each site year

Site	Year	Rainfall (cm)	Soil pH	Soil Texture	mg kg^{-1} P (0-15 cm)	mg kg^{-1} S (0-60 cm)
Brandon	2010	45.2	-	CL	5.2	4.3
	2011	7.1	8.2	CL	-[y]	-[y]
	2012	41.6	-	CL	7.0	9.9
Carman	2010	8.4	6.1	FSL	-[y]	-[y]
	2011	29.8	-	FSL	-[y]	-[y]
	2012	12.3	8.2	L/SiCL	17.3	6.1
Kelburn	2011	-	6.5	C	25.7	10.5
	2012	-	8.1	C	17.5	6.7
Lethbridge	2010	92.8	7.9	C/CL	-[y]	-[y]
	2011	51.5	7.3	C/CL	37.7	4.7[z]
	2012	28.6	7.3	C/CL	-[y]	-[y]
Normandin	2010	11	5.3	SiCL	-[y]	-[y]
	2011	43	5.8	SiCL	-[y]	-[y]
	2012	52.6	6.4	SiCL	-[y]	-[y]
Thunder Bay	2010	44.4	6.3	SiCL	-[y]	-[y]
	2011	32.2	6.4	SiCL	21.9	4.8
	2012	86.4	6.4	SiCL	-[y]	-[y]

[z] 0-30 cm depth

[y] Soil samples from these site years have not yet been analyzed by Agriculture and Agri-Food Canada

2.3.3 Plant Stand

Crop emergence date was determined to be when the seeded rows of canola first became visible in the control plots. Plant stand was determined by counting all seedlings in a two rows one meter in length at two locations in each plot. Plant stand was assessed at four weeks after emergence.

2.3.4 Early Season Biomass Accumulation

Biomass samples were taken when most of the plots reached the early flowering stage (GS61) (Canola Council of Canada 2011a). All the above ground biomass was cut in a one meter row at two locations in each plot. Samples were oven dried at 60°C for at least 24 hours, weighed and ground.

2.3.5 Seed Yield

Each plot was swathed using the Canola Time of Swathing Guide as a reference (Canola Council of Canada 2012). The swaths were harvested using a plot combine. The seed was cleaned and weighed to determine seed yield. Seed yield was not adjusted for moisture content.

2.3.6 Statistical Analysis

The Mixed Procedure in SAS 9.3 was used to conduct statistical analysis for the field experiment (SAS Institute, Inc. 2013). A one-way randomized complete block design ANOVA model was used to test the significance of the treatment effect at each site-year separately. Treatment was considered a fixed effect and block as a random effect. Assumptions regarding the conformity of the data were tested using Proc Univariate.

Data from each site year was tested for normality using the Shapiro-Wilk Statistic; all datasets followed a normal distribution; therefore, transformations were not required. Site years with unequal variance among treatments were corrected using the repeated statement. A Fisher's Protected LSD test was used to separate the treatment means. Letter groupings were assigned to treatments using a SAS macro (pdmix800) (Saxton 1998). Means were considered significantly different at $P < 0.05$. The Regression Procedure in SAS 9.3 was also used to analyse the linear regression between plant stand and yield at each site year using the treatment means (data in Appendix B).

2.4 Results and Discussion

2.4.1 Seedling Emergence

Fertilizer treatment effects on canola plant stand were significant at eight of 17 site-years (Table 2.3a, b, c). The plant stand of all the control treatments at each of these site years, with the exception of Lethbridge in 2011, was above the critical threshold of 40 plants m^{-2} (Table 2.3a, b, c). Although some fertilizer treatments caused statistically significant reductions in plant stand relative to the control at these sites, the damage may or may not be agronomically significant. A target of 40-200 plants m^{-2} is recommended by the Canola Council of Canada (2011b); therefore, if the fertilizer treatment does not reduce plant stand below the optimum range, yield potential may not be decreased.

2.4.1.1 Phosphorus Fertilizer Applied Alone. Uncoated MAP applied alone decreased plant stands relative to the control only at Carman in 2011 (Table 2.3a). The mean reduction in plant stand relative to the control was 8% with low MAP and 16% with high MAP at site years with significant treatment effects. There was no significant difference

Table 2.3a Plant stand (plants m^{-2}) means of canola four weeks after emergence by treatment at the Brandon and Carman, MB sites

	Brandon			Carman		
Treatment	2010	2011	2012	2010	2011	2012
Control	61	47	98^{ac}	68^{abcd}	105^{a}	75
Low AS	48	59	$64^{abcdefh}$	83^{a}	90^{abc}	63
Low ATS	66	55	$70^{abcdefh}$	73^{ab}	-	73
High AS	62	49	75^{cdefhi}	66^{abcd}	73^{de}	78
High ATS	56	31	58^{fh}	71^{abc}	-	62
Low MAP	66	53	78^{cdefij}	70^{abcd}	83^{bcd}	67
Low APP	34	43	84^{abcdg}	70^{abc}	-	79
Low cMAP	65	58	90^{abc}	60^{bcdef}	99^{abcd}	67
Low MES15	61	48	84^{abcdef}	59^{bcdef}	89^{b}	74
Low MAP/low AS	43	52	$81^{abcdefh}$	54^{bcdef}	83^{bc}	65
Low cMAP/low AS	51	53	116^{ab}	63^{abcde}	83^{bcd}	56
Low APP/low ATS	48	41	56^{h}	75^{ab}	-	57
Low MAP/high AS	49	43	55^{hj}	54^{bcdef}	55^{f}	68
Low cMAP/highAS	58	57	76^{cdefhi}	49^{cdef}	81^{abcdef}	55
Low APP/high ATS	44	48	58^{fgh}	65^{abcd}	-	74
High MAP	54	43	$83^{abcdefh}$	47^{def}	76^{bcdef}	64
High APP	43	48	74^{defj}	55^{bcdef}	-	57
High cMAP	54	59	94^{abcdef}	63^{abcde}	96^{ab}	65
High MAP/low AS	64	49	79^{bdegi}	42^{ef}	78^{bcdef}	63
High cMAP/low AS	67	51	96^{abcde}	49^{cdef}	82^{bcd}	65
High APP/low ATS	45	38	69^{efh}	66^{abcd}	-	67
High MES15	57	44	89^{abcg}	66^{abcd}	73^{cde}	59
High MAP/high AS	49	51	81^{abcdeg}	38^{f}	56^{ef}	65
High cMAP/high AS	55	48	83^{abcdef}	59^{bcdef}	87^{bcd}	73
High APP/high ATS	35	42	49^{h}	65^{abcd}	-	62
High MAP/high Vitasul	65	58	$87^{abcdefh}$	60^{bcdef}	76^{abcdef}	59
Mean	54	49	78	61	81	66
C.V.	44.9	28.1	29.0	55.8	20.8	23.2
df	25	25	25	25	17	25
F-value	1.3	1.1	12.1	1.7	13.1	0.8
$P > F$	NS	NS	.003	.0406	.0051	NS

[a-j] Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

Table 2.3b Plant stand (plants m^{-2}) means of canola four weeks after emergence by treatment at the Kelburn, MB and Lethbridge, AB sites

	Kelburn		Lethbridge		
Treatment	2011	2012	2010	2011	2012
Control	81	91	44	15^{abcdef}	101
Low AS	72	93	59	16^{abc}	91
Low ATS	*96*	91	44	16^{abcd}	84
High AS	63	93	53	16^{ab}	88
High ATS	83	74	46	11^{fg}	77
Low MAP	80	89	59	15^{abcde}	103
Low APP	87	98	56	13^{bcdefg}	76
Low cMAP	67	101	69	14^{abcdefg}	92
Low MES15	71	93	61	13^{cdefg}	88
Low MAP/low AS	57	108	46	16^{abcd}	83
Low cMAP/low AS	86	78	59	16^{abcde}	91
Low APP/low ATS	91	85	66	13^{bcdefg}	90
Low MAP/high AS	66	71	54	13^{cdefg}	102
Low cMAP/highAS	70	81	46	11^{g}	94
Low APP/high ATS	71	68	51	13^{bcdefg}	80
High MAP	78	93	76	16^{abcde}	91
High APP	71	83	56	16^{abc}	84
High cMAP	70	76	59	18^{a}	99
High MAP/low AS	76	93	66	13^{bcdefg}	87
High cMAP/low AS	68	64	61	13^{bcdefg}	95
High APP/low ATS	64	83	39	12^{efg}	76
High MES15	85	70	53	14^{bcdefg}	85
High MAP/high AS	68	69	38	12^{defg}	98
High cMAP/high AS	75	76	56	14^{bcdefg}	74
High APP/high ATS	80	90	58	13^{bcdefg}	90
High MAP/high Vitasul	86	68	63	13^{bcdefg}	93
Mean	75	84	55	14	89
C.V.	24.8	24.2	30.0	33.8	19.1
df	25	25	25	25	25
F-value	2.7	1.5	1.4	1.8	1.2
$P > F$	NS	NS	NS	.0341	NS

$^{a\text{-}g}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

Table 2.3c Plant stand (plants m^{-2}) means of canola four weeks after emergence by treatment at the Normandin, QB and Thunder Bay, ON sites

	Normandin			Thunder Bay		
Treatment	2010	2011	2012	2010	2011	2012
Control	113^{abcd}	87^{bc}	63^{abcd}	54	125	120^{abcde}
Low AS	120^{abc}	78^{bcd}	46^{abcd}	52	109	120^{abcde}
Low ATS	-	-	-	-	-	-
High AS	91^{efg}	80^{bcd}	63^{a}	54	106	105^{cdefg}
High ATS	-	-	-	-	-	-
Low MAP	109^{abcde}	86^{bc}	45^{bc}	48	121	129^{abc}
Low APP	-	-	-	-	-	-
Low cMAP	126^{a}	94^{ab}	57^{ae}	69	120	128^{abc}
Low MES15	101^{cdef}	76^{bcd}	42^{abcd}	75	117	103^{defg}
Low MAP/low AS	94^{defg}	74^{cde}	54^{abcd}	61	113	108^{bcdefg}
Low cMAP/low AS	120^{abc}	79^{bcd}	57^{abcd}	45	119	111^{bcdefg}
Low APP/low ATS	-	-	-	-	-	-
Low MAP/high AS	84^{fg}	56^{ef}	42^{bcde}	46	97	98^{efg}
Low cMAP/highAS	91^{efg}	66^{def}	56^{abcd}	36	115	130^{ab}
Low APP/high ATS	-	-	-	-	-	-
High MAP	98^{def}	68^{cdef}	46^{bc}	58	108	126^{abcd}
High APP	-	-	-	-	-	-
High cMAP	123^{ab}	108^{a}	53^{ab}	63	113	139^{a}
High MAP/low AS	84^{fg}	71^{cde}	34^{d}	47	104	106^{bcdefg}
High cMAP/low AS	113^{abcd}	85^{bc}	54^{ab}	48	124	116^{abcdef}
High APP/low ATS	-	-	-	-	-	-
High MES15	104^{bcde}	69^{cdef}	39^{bcde}	39	108	102^{defg}
High MAP/high AS	77^{g}	51^{f}	35^{cd}	42	92	89^{g}
High cMAP/high AS	89^{efg}	65^{def}	45^{bcde}	51	98	92^{fg}
High APP/high ATS	-	-	-	-	-	-
High MAP/high Vitasul	100^{def}	65^{def}	44^{bcde}	56	114	110^{bcdefg}
Mean	102	75	49	52	111	113
C.V.	18.4	23.9	30.5	30.8	14.5	17.9
df	17	17	17	17	17	17
F-value	4.5	4.0	18.0	2.3	1.5	2.6
$P > F$	<.0001	<.0001	.0026	NS	NS	.0039

$^{a\text{-}g}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

in plant stand between the high and low rates of MAP applied alone at any of the site years (Table 2.3a, b, c). Although the recommended rate of seed-placed MAP is generally restricted to approximately 22 kg P_2O_5 ha^{-1} (MAFRI 2007) the frequency and severity of plant stand reduction with the high rate of P fertilizer occurred only once in 17 site years. Therefore, applying twice the recommended rate could be considered a relatively low risk practice for the soils and seed-bed utilization in this study.

Coated MAP applied alone did not reduce plant stand relative to the control at any site years, and increasing the rate of cMAP from the low to high rate did not reduce plant stands (Table 2.3a, b, c). The average reduction in plant stand at all site years with any significant treatment effects was negligible (3% for the low rate, 0% for the high rate). In a laboratory study conducted by Qian et al. (2010), seed-placed MAP caused significant reductions in plant stand at 30-40 kg P_2O_5 ha^{-1}, while there was no reduction of plant stand with up to 80-100 kg P_2O_5 ha^{-1} with seed-placed cMAP. In the field, the polymer coating also appeared to be effective in decreasing the diffusion of salts from the granule and reducing the salt toxicity of MAP. For example, the low rate of MAP resulted in significantly lower plant stands than the low rate of cMAP at Normandin in 2012 (Table 2.3c). The high rate of MAP caused significantly lower plant stands than the high rate of cMAP at Normandin in 2010 and 2011 (Table 2.3c). Although there was no significant difference between MAP and cMAP at Carman in 2011, both MAP treatments reduced plant stand relative to the control, while the cMAP treatments did not (Table 2.3a). In all cases where cMAP appeared to be less toxic than uncoated MAP, a double disc opener was used (Table 2.1) which may have concentrated the fertilizer in the seed-row, increasing the risk of salt toxicity. Therefore, in situations where high rates of P are required, low SBU seeding equipment is used or the seed-bed is dry, cMAP may be used to reduce the risk of seedling damage.

Ammonium polyphosphate appeared to behave similarly to MAP at all sites except for Brandon in 2012 (Table 2.3a, b, c). The mean reduction in plant stand relative to the control at all site years with any significant treatment effects was similar for the low rates of MAP and APP (6% and 8%, respectively) and at the high rates (13% and 12%, respectively). However, the response to MAP and APP differed at Brandon in 2012. Although there were no significant differences in plant stand between the low rate of MAP and the low rate of APP at Brandon in 2012, the high rate of APP reduced plant stand relative to the control, while the high rate of MAP did not (Table 2.3a). Although the relative salt indices for MAP and APP are similar (26.7 and 20, respectively (Havlin et al. 2005)), the high rate of APP appeared to be more toxic than MAP at Brandon in 2012. We suspect that this may be due to minor differences in the position of the liquid fertilizer hose on the seeder, resulting in the delivery of the fertilizer droplets directly over the seed-row may have made reduced the plant stand to a greater extent than MAP granules, which may have been more scattered.

2.4.1.2 Sulphur Fertilizers Applied Alone. Ammonium sulphate applied alone at the low rate did not reduce plant stand relative to the control at any site years; however, the high rate of AS reduced plant stands at Carman in 2011 (Table 2.3a) and Normandin in 2010 (Table 2.3c). Although the mean reduction in plant stand at all site years with any significant treatment effects was similar for the low and the high rate of AS (6% and 11%, respectively), at Carman in 2011 and Normandin in 2010, there was a significant reduction in plant stand by increasing the rate of AS applied alone (Table 2.3 a, c). This indicates that applying AS above the recommended rate may cause seedling damage. Soil properties such as high soil pH, temperature or $CaCO_3$ content, or low CEC, low water content or coarse texture can increase the risk of NH_3 toxicity (Fenn and Kissel 1973), so the soil properties at these sites may have been a factor in increasing the toxicity of AS. To minimize risk of seedling damage, AS could be restricted to the low rate or placed away from the seed-row. Since SO_4^{2-} is mobile in the soil, alternative placement and timing options for AS are agronomically viable (Grant et al. 2012).

Similar to AS, the low rate of ATS did not reduce plant stands relative to the control (Table 2.3a, b, c). Increasing the rate of ATS, however, resulted in lower plant stands than the control at Brandon in 2012 (Table 2.3a). Similar to APP and MAP, the high rate of ATS seemed to be more damaging than AS at Brandon in 2012. Although there was no significant difference between AS and ATS when applied at the low rate at Brandon in 2012, the high rate of ATS reduced plant stand relative to the control, while the high rate of AS did not (Table 2.3a). In addition, the high rate of AS had a significantly greater plant stand than the high rate of ATS at Lethbridge in 2011 (Table 2.1). For the low rates of AS and ATS the mean reduction in plant stand relative to the control at all site years with any significant treatment effects was similar (2% and 5%, respectively); however, the difference between AS and ATS was greater at high rates (7% and 21%, respectively). Again, the salt indices are similar for AS and ATS (88.3 and 90.4, respectively (Havlin et al. 2005)), so the difference in response between sources may be due to the position of the liquid fertilizer band in the seed row.

2.4.1.3 Phosphorus and Sulphur Blends. The most frequent and severe reductions in plant stands relative to the control were due to applying P and S blends including a high rate of AS and/or a high rate of MAP (Table 2.3a, b, c). The mean reduction in plant stand relative to the control at all site years with any significant treatment effects increased with increasing rates of MAP and/or AS (14%, 30%, 25% and 34% for the low MAP/low AS, low MAP/high AS, high MAP/low AS and high MAP/high AS treatments, respectively). Because canola emergence decreases with increasing concentrations of salt and ammonia (Dowling, 1996), the high rate blends including AS or MAP were expected to have lower plant stands. Increasing the rate of P fertilizer in the blend did not always result in increased seedling damage, however. The blends including a high rate of MAP were not significantly different from the equivalent blends including a low rate of MAP. However, the high MAP/low AS blend reduced plant stand relative to the control, while the low MAP/low AS blend did not at Carman in 2010 and 2011 (Table 2.3a) and at Normandin in 2010 (Table 2.3c). The high MAP/high AS blend also reduced plant stand relative to the control while the low MAP/high AS blend did not at Carman in 2010 (Table 2.3a) and Thunder Bay in 2012 (Table 2.3c). Similarly, increasing the rate of cMAP in the blend did not result in frequent or severe reductions in plant stand (Table 2.3a, b, c); increasing the rate of cMAP in a blend with high AS significantly decreased plant stand at Thunder Bay in 2012 only (Table 2.3c).

Although increasing the rate of cMAP in the blend caused a significant reduction in plant stand at one in 17 site years, increasing the rate of AS in a blend with either cMAP or MAP significantly reduced plant stand more frequently (two site years for increasing AS with MAP and five site years for increasing AS with cMAP). For example, there were significant decreases in plant stand with the high rate of AS compared to the low rate of AS blended with low MAP (at Carman in 2011), with high MAP (at Normandin in 2011), with low cMAP (at Brandon in 2012, Lethbridge in 2011 and Normandin in 2010) and with high cMAP (at Normandin in 2010, 2011 and 2012) (Table 2.3a, b, c). Increasing the rate of AS in the cMAP/AS blend also reduced the plant stand more than increasing the rate of cMAP in the blend (3%, 18%, 11% and 18% for low cMAP/low AS, low cMAP/high AS, high cMAP/low AS and high cMAP/high AS blends, respectively, for all sites with any significant treatment effects). In laboratory studies, blending MAP with AS did not increase seedling damage compared to AS applied alone for *Brassica napus* varieties (Qian et al. 2012). Ammonium sulphate could be considered more toxic than equivalent rates of MAP because it has a higher salt index (88.3 for AS vs. 26.7 for MAP) (Havlin et al. 2005). As previously discussed, AS also has the potential to form NH_3, especially in soils with high pH or $CaCO_3$ content (Fenn and Kissel 1973). Although MAP can also produce a safening effect on AS by decreasing NH_3 formation, this was not observed at any of the site years, probably because soils at the sites were not calcareous and the NH_3 formation from AS was not substantial.

The novel fertilizers that contained ES were often less toxic than the high MAP/high AS blend (Table 2.3a, b, c). MicroEssentials S15 reduced plant stand only at Carman in 2011 (Table 2.3a), where increasing the rate of MES15 from the low to high rate significantly reduced plant stands. Although there was no significant difference between the low rate of MES15 and the low MAP/low AS blend, the high rate of MES15 had significantly greater plant stand than the high MAP/high AS blend at Carman and Normandin in 2010 (Table 2.3a, c). In addition, the high MAP/high AS blend reduced plant stand relative to the control, while the high rate of MES15 did not at Carman in 2010 (Table 2.3a), Normandin in 2010 and 2011 and Thunder Bay in 2012 (Table 2.3c). Similarly, these differences were also reflected in mean reduction in plant stand relative to the control from all site years with any significant treatment effects (16% for both low and high MES15, 14% for low MAP/low AS and 34% for high MAP/high AS).

The high MAP/high Vitasul blend also reduced plant stand compared to the control at only one site year, Normandin in 2010 (Table 2.3c). However, the high MAP/high Vitasul blend had significantly greater plant stands than high MAP/high AS blend at this site year (Table 2.3c). In addition, the high MAP/high AS blend reduced plant stand relative to the control, while the high MAP/high Vitasul blend did not at Carman in 2010 and 2011 (Table 2.3a), Normandin in 2010 and Thunder Bay in 2012 (Table 2.3c). The MAP/Vitasul blend was also not significantly different from the high rate of MAP applied alone at any of the site years (Table 2.3a, b, c), indicating that the reduction in plant stand was likely due solely to the MAP in this treatment. Similarly, the mean reduction in plant stand relative to the control from all site years with any significant treatment effects was equal for high MAP/high Vitasul (17%) and high MAP (16%), but lower than for high MAP/high AS (34%) and high MAP/low AS (25%).

Sulphur sources which contain ES, such as MES15 and Vitasul, may be less toxic than equivalent rates of AS because ES fertilizers are less toxic than SO_4^{2-} fertilizers. Unlike AS or ATS fertilizers, ES does not contain N, so there is no risk of ammonia toxicity and ES contains no salt and oxidizes slowly; therefore, ES has a much lower salt index than SO_4^{2-} (Grant et al. 2004). Because Vitasul is 100% ES and MES15 is 50% ES and 50% AS, these fertilizers could be less toxic than conventional SO_4^{2-} sources and therefore improve seedling emergence of canola. In addition, because the MES15 is a homogenous granule of N, P and S, the granules may distribute their AS component more evenly in the seed-row, decreasing the risk of AS toxicity, compared to AS granules.

As with the high rates of APP and ATS applied alone, the APP/ATS blends caused significant reductions in plant stand relative to the control at Brandon in 2012 (Table 2.3a). Increasing the rates of APP and ATS in the blend tended to decrease plant stands relative to the control (15%, 20%, 18%, 23% mean reductions for low APP/low ATS, low APP/high ATS, high APP/low ATS, and high APP/high ATS, respectively at all site years with any significant treatment effects). There was, however, no significant difference in plant stand when the rate of APP or ATS was increased from the low to high rate in the blend (Table 2.3a, b, c). The high APP/high ATS liquid blend had a significantly lower plant stand than the high MAP/high AS granular blend at Brandon in 2012 (Table 2.3a). In addition, although there was no significant difference between treatments, the low APP/low ATS blend reduced plant stand relative to the control while the low MAP/low AS treatment did not. Conversely, the high MAP/AS blends had significantly lower plant stands than the high APP/ATS blends at Carman in 2010. The difference in response between the liquid and granular blends may be site year specific due to reasons previously mentioned.

Although relatively high seeding rates were used in this study (150 seed m^{-2} or ~7 kg ha^{-1}), some fertilizer treatments reduced plant stand below or near the lower end of the optimum range of target plant densities. For example, at Carman in 2010 and at Normandin in 2012, where emergence of the control plots were 45% and 42% of seeds planted, respectively. If farmers reduce seeding rates to 3-4 kg ha^{-1}, which is lower than the recommended seeding rate of 5.9-9 kg seed ha^{-1} (Canola Council of Canada 2011b), only 70-90 seeds m^{-2} are planted. Under normal conditions, only 50% of the seeds will produce seedlings (53% emergence was the average in our study across all site years) and the plant stand will be near the lower range of optimal target plant populations. Under these conditions, applying seed-row fertilizer could reduce plant populations to levels that would be unsatisfactory. Very low plant stands can result in lower seed yield (McGregor

1987), delayed maturity in short growing season areas and decreased oil concentration (Grant et al. 2003a) and increased weed competition (Johnston et al. 2002).

2.4.2 Early-Season Biomass

Early-season biomass accumulation provides an estimate of the vegetative growth and yield potential of the crop. Seed-placed P and S fertilizers had both positive and negative effects on vegetative growth. If there was a nutrient response, seed-placed P and/or S fertilizers increased biomass accumulation; however, the seed-placed fertilizers may have also caused a reduction in plant stand in some situations, decreasing the capacity of the crop to reach yield potential. Treatment effects on early season biomass were significant at seven site years (Table 2.4a, b, c). Seed-placed P and S fertilizer treatments generally had a positive effect on dry matter accumulation relative to the control, except at Brandon in 2012 and Kelburn in 2012 (Table 2.4a, b). Some of the site years (Carman in 2010, Lethbridge in 2011, 2012 and Thunder Bay in 2010) had large coefficients of variation (>40%). The large variability at these site years may be the reason a treatment effect was not detected.

2.4.2.1 Phosphorus Fertilizers Applied Alone. The frequency of response to MAP applied alone was low. Although applying "starter P" with the seed can often increase early season growth by providing an available source of P in a favourable position for P uptake by roots (Grant et al. 2001), the only site year where the low rate of MAP increased biomass relative to the control was at Brandon in 2010 (Table 2.4a). The high rate of MAP did not increase biomass at this site (Table 2.4a). The lack of response to the high rate at this site did not appear to be related to a reduction in plant stand because the plant stand was not below the optimum range and was not significantly lower than for any

Table 2.4a Early season biomass yield (kg ha^{-1}) means of canola by treatment at the Brandon and Carman, MB sites

	Brandon			Carman		
Treatment	2010	2011	2012	2010	2011	2012
Control	2035^{g}	4609	3584^{efgh}	3350	1089	2528
Low AS	2644^{cdefg}	4047	5080^{ab}	4903	1138	3212
Low ATS	2381^{fg}	4229	4745^{abcde}	4415	-	2782
High AS	3018^{abcdef}	3591	3719^{cdefgh}	4011	1085	3211
High ATS	2421^{defg}	3862	4173^{abcdefg}	5083	-	3056
Low MAP	2780^{bcdef}	4726	3328^{fghi}	4350	987	2968
Low APP	2396^{efg}	4358	3032^{ghi}	3780	-	2941
Low cMAP	2622^{cdefg}	4378	4914^{abcde}	2984	1210	2670
Low MES15	3197^{abc}	4766	5046^{abc}	4151	1358	2858
Low MAP/low AS	2906^{abcdef}	4167	3611^{efgh}	3189	1225	2941
Low cMAP/low AS	3371^{ab}	5280	5049^{abc}	4003	1002	3130
Low APP/low ATS	2656^{bcdef}	4414	3944^{abcdefgh}	4167	-	2294
Low MAP/high AS	2859^{abcdef}	5116	2232^{i}	3085	1041	2974
Low cMAP/highAS	3125^{abcd}	4609	5219^{a}	3665	1305	3411
Low APP/high ATS	2966^{abcdef}	4237	4346^{abcdefg}	4508	-	3273
High MAP	2406^{defg}	5250	4160^{abcdefg}	3486	1033	2932
High APP	2409^{defg}	3830	4905^{abcde}	3837	-	2728
High cMAP	2742^{bcdefg}	4610	4432^{abcdef}	3509	1272	3194
High MAP/low AS	3540^{a}	4683	4105^{abcdefg}	3872	1362	2618
High cMAP/low AS	3217^{abc}	5299	3576^{efghi}	3375	1109	2785
High APP/low ATS	3103^{abcdef}	4243	4448^{abcdef}	4415	-	2650
High MES15	2931^{abcdef}	4813	4994^{abcd}	4645	1180	2801
High MAP/high AS	3064^{abcdef}	4285	3932^{abcdefgh}	3721	837	3019
High cMAP/high AS	2895^{abcdef}	4931	3651^{defgh}	2833	1314	3471
High APP/high ATS	2408^{defg}	3545	3861^{bcdefgh}	4787	-	3232
High MAP/high Vitasul	3112^{abcde}	4323	2726^{hi}	3991	1428	2421
Mean	2815	4469	4108	3927	1165	2927
C.V.	27.8	20.9	27.7	44.8	32.8	21.9
df	25	25	25	25	17	25
F-value	2.0	1.3	2.6	1.6	2.4	0.9
$P > F$	0.0124	NS	0.0007	NS	NS	NS

$^{a-i}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

Table 2.4b Early season biomass yield (kg ha^{-1}) means of canola by treatment at the Kelburn, MB and Lethbridge, AB sites

	Kelburn		Lethbridge		
Treatment	2011	2012	2010	2011	2012
Control	1142	3674^{abc}	2117^{g}	1158	1797
Low AS	1474	3619^{abd}	5029^{ab}	2631	1975
Low ATS	1101	3492^{bcd}	2744^{efg}	2353	1754
High AS	1182	3127^{def}	3639^{abcdefg}	2452	1987
High ATS	1310	2773^{e}	4413^{abcd}	2052	1524
Low MAP	1322	3515^{abcde}	3213^{cdefg}	4672	2323
Low APP	1468	3350^{abcde}	4238^{abcdef}	1613	1511
Low cMAP	1252	3568^{abcd}	3935^{abcdef}	1999	2420
Low MES15	1387	3796^{abcd}	5208^{a}	1946	1551
Low MAP/low AS	1540	3863^{ab}	2641^{fg}	2169	2014
Low cMAP/low AS	1534	3769^{abcde}	4078^{abcdef}	2088	2226
Low APP/low ATS	1442	3950^{abc}	4286^{abcdef}	1698	1937
Low MAP/high AS	1485	3009^{abcde}	4553^{abcd}	1903	2193
Low cMAP/highAS	1460	3168^{cf}	3854^{abcdef}	1775	1832
Low APP/high ATS	1552	3344^{abcde}	3383^{abcd}	2828	1573
High MAP	1825	3833^{abcd}	3478^{bcdefg}	2250	2272
High APP	1322	3518^{abcde}	3479^{bcdefg}	2435	3115
High cMAP	1350	3944^{ab}	4338^{abcde}	2887	2044
High MAP/low AS	1545	3299^{abcde}	4441^{abcd}	2741	1933
High cMAP/low AS	1782	2969^{abcde}	4435^{abcd}	2274	1855
High APP/low ATS	1535	3285^{abcde}	3839^{abcdef}	2251	2032
High MES15	1610	3197^{abcde}	4835^{abc}	3083	2188
High MAP/high AS	1611	3604^{abcd}	3008^{defg}	2379	2537
High cMAP/high AS	1513	3429^{bcd}	4409^{abcde}	2882	2580
High APP/high ATS	1676	4039^{a}	4688^{abc}	3402	2384
High MAP/high Vitasul	1403	3527^{abcde}	4303^{abcdef}	2155	3692
Mean	1455	3487	3945	2387	2125
C.V.	29.2	17.3	33.7	54.2	40.2
df	25	25	25	25	25
F-value	0.8	5.1	1.7	1.4	1.5
$P > F$	NS	0.0493	0.045	NS	NS

$^{a\text{-}g}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

Table 2.4c Early season biomass yield (kg ha^{-1}) means of canola by treatment at the Normandin, QE and Thunder Bay, ON sites

	Normandin			Thunder Bay		
Treatment	2010	2011	2012	2010	2011	2012
Control	2281^{cdef}	1874^{f}	1618^{bc}	1539	1927	2887
Low AS	2328de	1891^{f}	1673^{bc}	1069	2501	3165
Low ATS	-	-	-	-	-	-
High AS	2376^{cde}	1732^{f}	1368^{c}	1660	2704	3444
High ATS	-	-	-	-	-	-
Low MAP	2980^{abcde}	2121^{def}	1921^{abc}	1752	2115	3148
Low APP	-	-	-	-	-	-
Low cMAP	2229^{e}	2153^{def}	1971^{abc}	1411	2733	3422
Low MES15	2678^{bcd}	2204^{cdef}	1949^{abc}	1792	2941	3738
Low MAP/low AS	2765^{abcde}	2495^{bcde}	2274^{ab}	1297	2908	3434
Low cMAP/low AS	3109^{a}	2501^{bcde}	1703^{bc}	1168	2433	3265
Low APP/low ATS	-	-	-	-	-	-
Low MAP/high AS	2809^{abc}	2521^{bcde}	1960^{abc}	1528	2794	3097
Low cMAP/highAS	2767^{abc}	2070^{ef}	1578^{bc}	1361	2950	3882
Low APP/high ATS	-	-	-	-	-	-
High MAP	2886^{abf}	2166^{def}	1941^{abc}	1489	3039	3478
High APP	-	-	-	-	-	-
High cMAP	2715^{abcde}	2600^{abcd}	2473^{a}	1781	2410	3080
High MAP/low AS	2549^{abcde}	2704^{abc}	1686^{bc}	1379	2865	3025
High cMAP/low AS	3048^{ab}	2898^{ab}	2571^{a}	1136	2836	3502
High APP/low ATS	-	-	-	-	-	-
High MES15	3306^{ab}	2764^{ab}	2056^{abc}	1664	3194	3319
High MAP/high AS	2829^{abcde}	2991^{ab}	1698^{bc}	1107	2295	3338
High cMAP/high AS	2901^{abcde}	3054^{a}	2189^{ab}	950	2759	3962
High APP/high ATS	-	-	-	-	-	-
High MAP/high Vitasul	2529^{bcde}	2506^{bcde}	2051^{abc}	1012	2798	3024
Mean	2727	2402	1927	1394	2678	3345
C.V.	18.0	21.6	37.2	48.5	24.4	21.5
df	17	17	17	17	17	17
F-value	5.4	4.8	1.6	0.4	1.4	0.7
$P > F$	0.0325	<0.0001	0.0938	NS	NS	NS

$^{a\text{-}f}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

other treatment, including the control. This is different from Grant et al. (2009), who found that 11 kg P_2O_5 ha^{-1} side-banded MAP often increased early season canola biomass accumulation compared to the control and the higher rate of 22 kg P_2O_5 ha^{-1} often further increased biomass. Under laboratory conditions, Schoenau et al. (2005) and Qian et al. (2010) found that up to 40 kg P_2O_5 ha^{-1} of seed-placed MAP increased early season canola biomass accumulation because there was no significant reduction in plant stand up to this rate. The concentration of soil P could have been sufficient at our sites and the additional P fertilizers may not have resulted in greater biomass because the soil provided sufficient P for crop demand until this point. In addition, there may not have been a response to "starter P" at most sites because the seeding dates were relatively late and soil temperature likely would not have limited soil P diffusion.

Salt and NH_3 toxicity can also delay emergence (Dowling 1996); therefore, although there was no significant reduction in plant stand with the high rate of MAP, the plants may have developed slower, reducing the rate of biomass accumulation. In a similar experiment conducted under controlled environment conditions, canola plants exposed to the high rate of MAP and/or AS emerged more slowly during the first two weeks after emergence (see Chapter 3). However, in the growth chamber experiment, seedling emergence for most treatments stopped and plant stands stabilized after two weeks. Therefore, measuring plant stands at two weeks (Appendix A, Table A.1) and four weeks after emergence (Table 2.3a, b, c) in the field study may not have captured the effect of seedling toxicity on the rate of canola emergence and development.

The frequency of increase in biomass compared to the control was similar for low rates of cMAP and MAP (1 of 17 site years), but more frequent for high rates of cMAP (3 of 17 site years) than MAP (0 of 17 site years) (Table 2.4a, b, c). Similarly, under controlled environment conditions, P uptake and dry matter yield of barley was greater with cMAP than MAP at 52 days after seeding, indicating that P release of cMAP matched plant requirements more effectively than MAP (Pauly et al. 2002). Coated MAP may be superior to MAP in increasing early season biomass accumulation for canola in our field study as well. For example, the low rate of cMAP had significantly greater biomass than the low rate of MAP at Brandon in 2012 and the high rate of cMAP increase biomass relative to the control while the high rate of MAP did not at Lethbridge in 2010 and Normandin in 2011 and 2012 (Table 2.4b, c). The difference between MAP and cMAP at these P responsive sites may have been due to subtle effects of seedling toxicity with the high MAP treatments. Though the difference in stand reduction was not significant between MAP and cMAP, sub-lethal salt stress from uncoated MAP may have slowed the emergence and development of seedlings.

Conversely, under controlled environment conditions, Qian et al. (2010) found very little difference in dry matter yield between seed-placed cMAP and MAP at early growth stages. This was attributed to the seedling damage that occurred with higher rates of seed-placed MAP and the potential adsorption and precipitation of the small amount of P that had been released from cMAP. However, increasing the rate of cMAP may have overcome this challenge of P retention because, unlike MAP, there appeared to be a positive response to increasing the rate of cMAP. While there was no significant difference in biomass accumulation between the low and the high rate of cMAP, the high rate of cMAP increased biomass accumulation relative to the control while the low rate did not at Normandin in 2011 and 2012 (Table 2.3c).

Like MAP, there was a low frequency of response to APP applied alone. The low rate of APP significantly increased biomass relative to the control only at Lethbridge in

2010, while the high rate of APP did not at this site (Table 2.4b). There was no reduction in plant stand by increasing the rate of APP at this site, so it is unclear why the higher rate did not increase biomass accumulation. Conversely, although neither rate of APP increased biomass accumulation relative to the control at Brandon in 2012, the high rate of APP had significantly greater biomass accumulation than the low rate of APP (Table 2.4a), perhaps due to a nutrient response to a greater P concentration.

Comparing MAP to APP, there was no significant difference in biomass accumulation. However, at Lethbridge in 2010, the low rate of APP increased biomass compared to the control while the low rate of MAP did not (Table 2.2). The opposite occurred at Brandon in 2010 (Table 2.4a). The different responses at these two sites cannot be explained by significant difference in plant stand, so perhaps there was an inconsistent difference in availability between the two sources of P at these sites. Although Leytem and Westermann (2005) found that APP can be more effective in increasing soil P and shoot P accumulation than MAP in barley, total biomass accumulation was not significantly different.

2.4.2.2 Sulphur Fertilizers Applied Alone. As with P fertilizers, the frequency of biomass response relative to the control for AS applied alone was low. The low rate of AS increased biomass accumulation relative to the control at Brandon in 2012 (Table 2.4a) and Lethbridge in 2010 (Table 2.4b). The high rate of AS increased biomass accumulation relative to the control at Brandon in 2010 but decreased biomass accumulation at Kelburn in 2012 (Table 2.2).

Although the high rate of AS increased biomass relative to the control while the low rate did not at Brandon in 2010 (Table 2.4a), increasing the rate of AS from the low to high rate had negative effects on biomass accumulation at other sites. At Brandon in

2012, the high rate of AS had significantly lower biomass accumulation than the low rate of AS (Table 2.4a); at Kelburn in 2012, although the low rate of AS did not increase biomass relative to the control, the high rate decreased biomass relative to the control (Table 2.4b); and at Lethbridge in 2010, the low rate of AS increased biomass accumulation relative to the control while the high rate did not (Table 2.4b). Similarly, in field studies, Grant et al. (2003b) found that sometimes 20 kg S ha^{-1} seed-placed AS could produce less biomass accumulation compared to surface broadcast AS because seed-placed AS significantly reduced the plant stand. Although increasing the rate of AS had negative effects on biomass accumulation at Brandon in 2012, Kelburn in 2012 and Lethbridge in 2010, there was little or no difference in plant stand between the low and the high rates of AS. However, the seedling toxicity of the high rate of AS may have caused slower rates of emergence and development and could have been a factor in reducing biomass accumulation.

Comparing ATS and AS, the response was variable and depended on the site. At Brandon in 2010, the high rate of AS increased biomass accumulation relative to the control while the high rate of ATS did not (Table 2.4a). Similarly, at Brandon in 2012, the low rate of AS increased biomass while the low rate of ATS did not (Table 2.4a). The response to ATS was similar to that of AS at Kelburn in 2012; both the high rate of ATS and AS decreased biomass relative to the control while the low rate did not (Table 2.4b). Conversely, the response to ATS and AS was mixed at Lethbridge. The low rate of AS had significantly greater biomass than the low rate of ATS but the high rate of ATS increased biomass relative to the control while the high rate of AS did not (Table 2.4b). Because $S_2O_3^{2-}$ rapidly converts to SO_4^{2-} in the soil (Janzen and Bettany 1986), ATS is considered to be as effective as AS in increasing S uptake and biomass accumulation in canola in the year of application (Grant et al. 2003b). Since the availability of AS and ATS should be similar and there were no large differences in plant stands at these sites, it is unclear why there was a different response to these S sources at different rates and sites.

2.4.2.3 Phosphorus and Sulphur Blends. In general, the P and S blends increased biomass accumulation compared to the control more frequently than P or S applied alone (Table 2.4a, b, c) indicating that both nutrients were likely limiting to some degree at most of the sites. In addition, Goos et al. (2001b) found that blending an acid-forming S fertilizer such as AS, ATS or ES with APP can improve early season P uptake and biomass accumulation in wheat. Although P uptake may have been improved by adding S to the P treatments, it is difficult to distinguish if the biomass response was due to improved P uptake or a nutrient response to supplemental S.

Both the source and rate of P and S affected biomass accumulation. Increasing the rate of P fertilizer in the blend generally increased biomass accumulation. For example, high MAP/low AS had significantly greater biomass than low MAP/low AS at Lethbridge in 2010 (Table 2.4b) and high MAP/high AS had significantly greater biomass than low MAP/high AS at Brandon in 2012 (Table 2.4a). However, at Lethbridge in 2010, the low MAP/high AS treatment increased biomass relative to the control, while the high MAP/high AS treatment did not (Table 2.4b). Perhaps the lack of the response at the higher rate at this site year was due to a very low plant stand resulting from the high MAP/high AS treatment. These results are consistent with results from Qian et al. (2012), who found that increasing the rate of MAP from 15 kg P_2O_5 ha^{-1} to 30 kg P_2O_5 ha^{-1} in a blend with AS did not consistently reduce early season biomass accumulation.

Increasing the rate of cMAP in a blend had inconsistent effects on biomass accumulation. High cMAP/low AS had significantly greater biomass accumulation than low cMAP/low AS at Normandin in 2012 and high cMAP/high AS had significantly greater biomass than low cMAP/high AS at Normandin in 2011. However, the low rate cMAP blends increased biomass accumulation relative to the control while the high rate cMAP blends did not at Brandon in 2012 (Table 2.4a). There were no significant differences in plant stand between these treatments, so it is unclear why there was no response to the additional cMAP applied at Brandon in 2012.

In general, cMAP blends appeared to be more effective than MAP blends in increasing biomass yield at Brandon in 2012, Lethbridge in 2010 and Normandin in 2010, 2012 (Table 2.4 a, b, c). Biomass accumulation was significantly greater with low cMAP blends than low MAP blends at Brandon in 2012 (Table 2.4a). In addition, low cMAP/low AS increased biomass relative to the control while low MAP/low AS did not at Lethbridge and Normandin in 2010 (Table 2.4b, c). Similarly, the high cMAP/low AS blend increased biomass relative to the control, while the high MAP/low AS blend did not at Normandin in 2010 and 2012 (Table 2.4c) and the high cMAP/high AS blend increased biomass relative to the control, while the high MAP/high AS blend did not at Lethbridge in 2010 (Table 2.4b). The greater biomass accumulation with the cMAP blends at the Normandin sites was likely due to the significantly higher plant stand from the cMAP blends in comparison to the MAP blends. Although the differences in plant stand at Lethbridge and Brandon were not significant, the plant stands tended to be greater with the cMAP blends than the MAP blends. As previously discussed with P fertilizers applied alone, sub-lethal effects of MAP may have resulted in slower seedling emergence and development, reducing the biomass accumulation compared to cMAP.

Unlike P fertilizers, increasing the rate of AS from 9 to 18 kg S ha^{-1} in the blend did not generally have positive effects on biomass accumulation, perhaps due to seedling toxicity at some sites. Low MAP/low AS had significantly greater biomass accumulation than low MAP/high AS at Brandon in 2012 (Table 2.4a). Similarly, the high MAP/low AS blend increased biomass compared to the control while the high MAP/high AS blend did not at Lethbridge in 2010 (Table 2.4b). At both these sites the blend with the high rate of AS had lower plant stands than blends with the low rate of AS, so the poorer plant stand may not have been capable of compensating, even with the additional nutrients. Increasing the rate of AS with cMAP also had negative effects on biomass at Normandin. For example, the low cMAP/low AS blend increased biomass relative to the control while the low cMAP/high AS blend did not in 2010 and 2011 (Table 2.4c). Similarly, the high cMAP/low AS blend increased biomass relative to the control while the high cMAP/high AS blend did not in 2010 and 2012 (Table 2.4c). The lower biomass accumulation with the high rate blends at Normandin in 2010 may be explained by the significant difference in plant stand between the low and the high rates of AS blends (Table 2.3c). However, at the other sites where no significant reduction in plant stand occurred, delayed emergence and development due to seedling toxicity of the high rate of AS may have reduced the capacity of the crop to reach maximum biomass yield potential.

The application of MES15 increased biomass accumulation compared to the control more frequently than the equivalent rate of MAP/AS blends (Table 2.4a, b, c). Increasing the rate of MES15 significantly increased biomass accumulation at Normandin in 2011 and at Normandin in 2010, the high rate of MES15 increased biomass relative to the control while the low rate did not (Table 2.4c). The higher rate may have been required to satisfy the S requirement of the crop and the low salt and NH_4^+ content of

MES15 granules may have minimized the risk of seedling toxicity problems. Similarly, when comparing MES15 to MAP/AS blends at Normandin in 2010, the low MAP/low AS blend increased biomass relative to the control while the low MES15 did not (Table 2.4c). However, at the high rate, MES15 increased biomass relative to the control while the high MAP/high AS blend did not (Table 2.4c). This could be due to the large reduction in plant stand with the high MAP/high AS blend, while there was no significant difference in plant stand comparing the low rates (Table 2.3c). At Lethbridge in 2010 and Brandon in 2012, both the low and the high rate of MES15 appeared at be superior to the equivalent rates of MAP/AS (Table 2.4a, b). Again, the difference in plant stand between these sources at these sites could explain the greater biomass accumulation with MES15. There may have been adequate SO_4^{2-} in the MES15 and soil to supply the crop with SO_4^{2-} for the first part of the growing season, and therefore, there was a lack of response to the additional SO_4^{2-}-S supplied from the AS.

There was a higher frequency of response for high MAP/high Vitasul than for high MAP applied alone, indicating that some of the S_o may have been oxidized at Brandon and Lethbridge in 2010 and at Normandin in 2011. There was no significant difference between high MAP/high Vitasul and any of the high MAP/AS treatments at these sites. However, the high MAP/high Vitasul increased biomass relative to the control while the high MAP/high AS blend did not at Lethbridge in 2010. The lack of response with high MAP/high AS may have resulted from seedling toxicity effects on plant development. There was significantly lower biomass accumulation with high MAP/high Vitasul than with high MAP alone and high MAP/low AS at Brandon in 2012. We suspect, though, that differences between the treatments were due to the significantly lower plant stand in this treatment, and not a lack of S response.

Although AS provides an immediate and fully available source of SO_4^{2-}, it has a greater risk of seedling damage compared to ES fertilizers and AS can reduce the plant stand, reducing total biomass accumulation. In a situation without the risk of seedling injury, Grant et al. (2003b) found that broadcasting AS and a blended SO_4^{2-}/ES product at a rate of 20 kg S ha^{-1} resulted in similar dry matter yields; however, broadcast AS resulted in higher biomass yields than broadcast Tiger 90 (a bentonite ES). The ES was not oxidized at a rate sufficient to meet crop demand in the year of application. However, when AS and Tiger 90 were both seed-placed, dry matter yields were similar, likely because the seed-placed AS caused seedling damage, which offset any nutritional benefits.

As with MAP/AS blends, blending APP and ATS generally increased the frequency of response relative to the control compared to either APP or ATS applied alone. However, increasing the rate of APP or ATS in the blend did not increase biomass accumulation. In fact, at Brandon in 2010, low APP/high ATS and high APP/low ATS increased biomass relative to the control while high APP/high ATS did not (Table 2.4a). The lack of response with the high APP/high ATS blend is likely due to the severe reduction in plant stand (the plant stand was below the optimum range) (Table 2.3a).

The response to APP/ATS compared to MAP/AS blends differed again by site year. At Lethbridge in 2010, the APP/ATS blends were superior to the MAP/AS blends. For example, the low APP/low ATS blend increased biomass relative to the control while the low MAP/low AS blend did not and the high APP/high ATS had significantly more biomass than the high MAP/high AS blend (Table 2.4b). Conversely, the APP/ATS blends were inferior to the MAP/AS blends at Brandon. In 2012, the low MAP/high AS blend had significantly more biomass than the low APP/high ATS blend and in 2010, the high MAP/high AS blend increased biomass relative to the control while the high APP/high ATS blend did not (Table 2.4a). These trends are similar to the conventional P and S sources applied alone. Again, the difference in plant stand between liquid and granular blends for these rates was not significant, so it is unclear why there was a difference in biomass accumulation between sources at these sites.

2.4.3 Seed Yield

The effect of S and P fertilization on canola seed yield was significantly positive at nine site years (Table 2.5a, b, c). There were no decreases relative to the control; however, some of the high rates were less effective in increasing the seed yield, compared to the low rates. The lack of response to the higher rate of fertilizer could have been due seedling toxicity; however, the relationship between plant stand and yield was not significant or positive at most site years (see Appendix C, Table C.1). Using plant stand as a tool to predict seed yield response to seed-placed fertilizers is difficult because the yield response depends on balancing optimum plant stand with adequate nutrition. Because canola is capable of compensating for lower plant densities by increasing the number of pods per plant, seeds per pod and seed weight (Krogman and Hobbs 1975), lower plant densities caused by seed-placed fertilizer do not consistently reduce seed yield (Grant et al. 2010; Johnston et al. 2001, 2002). However in some cases, it appears that although higher rates of seed-placed P and S fertilizers did not reduce plant stand below the optimum range, seed yield was not as high as for low rates. We suspect that this may have been due to sub-lethal effects of the fertilizer on emergence, growth and development early in the growing season that could have reduced the capacity of the crop to reach its yield potential.

2.5a Seed yield (kg ha^{-1}) means of canola by treatment at the Brandon and Carman MB sites					
	Brandon		Carman		
Treatment	2010	2012	2010	2011	2012
Control	1277^{h}	738^{h}	1950	1249	1703
Low AS	2047^{abcdefg}	795^{h}	2036	1488	1668
Low ATS	1757^{defgh}	1058^{fgh}	1935	-	1721
High AS	1936^{bcdefg}	1082^{efgh}	2001	1391	1873
High ATS	1758^{defgh}	792^{h}	2059	-	1874
Low MAP	1948^{bcdefg}	1408^{bcdef}	2058	1492	1698
Low APP	1563^{fgh}	892^{gh}	2037	-	1661
Low cMAP	1471^{gh}	1396^{bcdef}	1988	1445	1640
Low MES15	2114^{abcdefg}	1478^{abcdef}	2037	1619	1704
Low MAP/low AS	2094^{abcdefg}	1367^{bcdef}	1845	1510	1881
Low cMAP/low AS	2205^{abcdef}	1574^{abcd}	2029	1600	1861
Low APP/low ATS	1854^{cdefgh}	1155^{defgh}	2100	-	1564
Low MAP/high AS	2471^{abc}	1719^{abc}	1859	1409	1867
Low cMAP/highAS	2484^{abc}	1581^{abcd}	2111	1537	1657
Low APP/high ATS	2194^{abcdef}	1427^{bcdef}	2112	-	1816
High MAP	1816^{defgh}	1472^{abcdef}	2031	1462	1630
High APP	1637^{efgh}	1066^{fgh}	1982	-	1669
High cMAP	1519^{gh}	1510^{abcde}	1999	1525	1754
High MAP/low AS	2570^{ab}	1616^{abc}	2005	1476	1826
High cMAP/low AS	2649^{a}	1867^{a}	1951	1570	1364
High APP/low ATS	1927^{bcdefgh}	1314^{bcdefg}	2096	-	1766
High MES15	2284^{abcde}	1726^{ab}	2085	1607	1682
High MAP/high AS	2689^{a}	1563^{abcd}	1883	1319	1781
High cMAP/high AS	2356^{abcd}	1503^{abcde}	2015	1368	1909
High APP/high ATS	2057^{abcdefg}	1286^{cdefg}	2046	-	1762
High MAP/high Vitasul	2539^{ab}	1420^{bcdef}	2176	1530	1706
Mean	2047	1339	2016	1478	1732
C.V.	32.3	30.4	8.4	14.4	12.5
df	25	25	25	17	25
F-value	2.8	3.9	0.9	1.6	3.0
P > F	.0003	<.0001	NS	NS	NS

$^{a-h}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

2.5b Seed yield (kg ha^{-1}) means of canola by treatment at the Kelburn, MB and Lethbridge, AB sites

	Kelburn		Lethbridge		
Treatment	2011	2012	2010	2011	2012
Control	1380^{gh}	1573	483^{h}	218	1170
Low AS	1830^{abcdef}	1563	1096^{abcd}	807	1568
Low ATS	1743^{abcdefgh}	1475	683^{fgh}	793	1508
High AS	1588^{cdefgh}	1606	870^{abcdefg}	802	1657
High ATS	1702^{bcdefgh}	1621	886^{abcdefg}	532	1677
Low MAP	1569^{defgh}	1545	916^{abcdefg}	846	1636
Low APP	1538^{efgh}	1567	1103^{abcd}	425	1579
Low cMAP	1464^{fgh}	1646	1081^{abcde}	608	1621
Low MES15	1335^{h}	1636	1038^{abcdef}	572	1735
Low MAP/low AS	1892^{abcde}	1583	748^{defgh}	772	1508
Low cMAP/low AS	2007^{abc}	1579	981^{abcdefg}	835	1562
Low APP/low ATS	1693^{bcdefgh}	1581	928^{abcdefg}	464	1712
Low MAP/high AS	1946^{abcde}	1497	1014^{abcdefg}	735	1699
Low cMAP/highAS	1857^{abcdef}	1594	800^{cdefgh}	594	1353
Low APP/high ATS	1775^{abcdefgh}	1567	800^{bcdefgh}	639	1429
High MAP	1851^{abcdef}	1615	831^{bcdefgh}	743	1535
High APP	1662^{bcdefgh}	1521	933^{abcdefg}	990	2032
High cMAP	1606^{cdefgh}	1704	1032^{abcdef}	1143	1577
High MAP/low AS	2051^{ab}	1511	1170^{abc}	1258	1788
High cMAP/low AS	1985^{abcd}	1602	1094^{abcd}	830	1676
High APP/low ATS	1887^{abcde}	1696	637^{gh}	725	1940
High MES15	2070^{ab}	1573	708^{efgh}	930	1825
High MAP/high AS	2147^{a}	1515	916^{abcdefg}	759	2073
High cMAP/high AS	1786^{abcdefgh}	1578	1253^{a}	957	1475
High APP/high ATS	1792^{abcdefg}	1490	1096^{abcd}	1207	1813
High MAP/high Vitasul	1929^{abcde}	1537	1186^{ab}	660	2120
Mean	1772	1576	934	763	1664
C.V.	20.4	10.5	33.6	48.4	35.1
df	25	25	25	25	25
F-value	2.0	0.5	1.9	1.3	0.7
P > F	.0147	NS	.0213	NS	NS

$^{a\text{-}h}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

2.5c Seed yield (kg ha^{-1}) means of canola by treatment at the Normandin, QE and Thunder Bay, ON sites

	Normandin			Thunder Bay		
Treatment	2010	2011	2012	2010	2011	2012
Control	3172^{gh}	2836^{i}	3974^{g}	1361^{j}	2341	1597^{f}
Low AS	3317^{cdefgh}	3491^{efg}	4332^{def}	$2743^{abcdefghi}$	2834	2810^{abc}
Low ATS	-	-	-	-	-	-
High AS	3490^{abcde}	3205^{h}	4270^{f}	2511^{cdefh}	2799	2737^{abcd}
High ATS	-	-	-	-	-	-
Low MAP	3141^{h}	3297^{gh}	4302^{ef}	$2682^{abcdefg}$	2712	2445^{cde}
Low APP	-	-	-	-	-	-
Low cMAP	3279^{efgh}	3162^{h}	4375^{def}	$2345^{abcdefghij}$	2532	1935^{ef}
Low MES15	3518^{abcd}	3743^{cde}	4333^{def}	2939^{abcde}	2759	2370^{cde}
Low MAP/low AS	3542^{abc}	3972^{abc}	4601^{abcd}	3752^{abc}	2969	2683^{abcd}
Low cMAP/low AS	3515^{abcd}	3729^{cde}	4524^{bcdef}	1862^{ij}	2787	2785^{abcd}
Low APP/low ATS	-	-	-	-	-	-
Low MAP/high AS	3497^{abcde}	3766^{bcd}	4542^{bcde}	3157^{b}	3212	2677^{abcd}
Low cMAP/highAS	3637^{a}	3541^{defg}	4509^{cdef}	2336^{efghi}	3162	2928^{abc}
Low APP/high ATS	-	-	-	-	-	-
High MAP	3376^{bcdefg}	3575^{def}	4503^{cdef}	$2384^{cdefghi}$	2856	2220^{de}
High APP	-	-	-	-	-	-
High cMAP	3253^{fgh}	3370^{fgh}	4318^{ef}	3042^{abcd}	2838	2488^{bcde}
High MAP/low AS	3495^{abcde}	4005^{ab}	4705^{abc}	3459^{a}	3229	2693^{abcd}
High cMAP/low AS	3528^{abc}	4182^{a}	4872^{a}	2381^{defghi}	3314	3097^{a}
High APP/low ATS	-	-	-	-	-	-
High MES15	3568^{ab}	4008^{ab}	4787^{ab}	2159^{fghi}	2820	2728^{abcd}
High MAP/high AS	3455^{abcdef}	3838^{bc}	4704^{abc}	1903^{gijk}	3086	3042^{ab}
High cMAP/high AS	3575^{ab}	3971^{abc}	4742^{abc}	1872^{hijk}	3155	3151^{a}
High APP/high ATS	-	-	-	-	-	-
High MAP/high Vitasul	3297^{defgh}	3755^{bcd}	4492^{cdef}	2327^{efghi}	3193	2378^{cde}
Mean	3425	3636	4493	2512	2922	2598
C.V.	7.7	10.6	8.6	26.1	15.4	20.3
df	17	17	17	17	17	17
F-value	3.4	15.6	5.4	196.1	1.5	4.0
P > F	.0004	<.0001	<.0001	.0001	NS	<.0001

$^{a\text{-}k}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

2.4.3.1 Phosphorus Applied Alone. Monoammonium phosphate applied alone frequently increased seed yield (seven site years with the low rate, six site years with the high rate). At some sites, the low rate, which is the maximum recommended rate of seed-row MAP was yield limiting. At Normandin in 2010 and 2011, increasing the rate of MAP applied alone significantly increased seed yield (Table 2.5c). Similarly, the high rate of MAP increased seed yield compared to the control, while the low rate did not at Kelburn in 2011 (Table 2.3b). Although the numerical means for plant stand for the high rate of MAP were less than for the control at these sites (Table 2.3b, c), the reduction was not significant statistically or agronomically. The low rate of MAP increased seed yield relative to the control, while the high rate of MAP did not at Brandon and Lethbridge in 2010 (Table 2.5a, b). However, plant stands were not affected by treatment at these site years (Table 2.3a, b); therefore, it is unclear why the high rate of MAP did not increase seed yield but the low rate of MAP did. Seedling emergence and development may have been delayed by the high rate of MAP, reducing the capacity of the crop to reach yield potential.

The low rate of cMAP applied alone also appeared to be yield limiting at some site years. Although there were no significant differences in seed yield between the low and high rates of cMAP, the high rate of cMAP increased seed yield relative to the control while the low rate of cMAP did not at Thunder Bay in 2010 and 2011 (Table 2.5c). The low rate of cMAP may not have provided sufficient amounts of P to satisfy crop demand. Leytem and Westermann (2005) suggested that available P from cMAP might be insignificant on low P or high CEC soils where it is quickly retained. Because the rate of P release from cMAP is temperature dependent (Zang et al. 2000), Qian et al. (2010) suggested that P release in cold soils in spring may result in low P availability.

Phosphorus deficiency early in the growing season can result in irreversible reductions in crop growth (Grant et al. 2001), and subsequently, yields can be compromised. At Thunder Bay in 2010 and 2011, however, the low and high rates of cMAP had similar accumulation of early season biomass (Table 2.4c) so perhaps there was insufficient P available from the low cMAP treatment later in the growing season to meet crop demand.

Although there were no significant differences between MAP and cMAP on seed yield, the low rate of cMAP did not increase seed yield compared to the control as frequently as the low rate of MAP (four vs. seven site years) (Table 2.5a, b, c). The low rate of MAP increased seed yield relative to the control, while the low rate of cMAP did not at Brandon in 2010 nor at Thunder Bay in 2010 and 2012 (Table 2.5a, c). There were no differences in plant stand or early season biomass accumulation (Tables 2.3, 2.4) which could explain why the low rate of MAP was superior to the low rate of cMAP at these site years. Therefore, late season availability of P from cMAP may have been less than for uncoated MAP. Although MAP forms insoluble DCPD relatively quickly in alkaline soils (Doyle and Cowell 1993), canola plants can acidify the rhizosphere (Trolove et al. 2003; Grant et al. 2001) and dissolve DCPD throughout the growing season. Perhaps there may be no benefit from the cMAP delivering soluble P slowly over the growing season because canola is efficient at utilizing fertilizer P. The polymer coating may actually restrict diffusion of available P from the granule, making it unable to satisfy canola's demand for P during the growing season. Therefore, when applied in the seed-row at recommended rates, uncoated MAP may be more reliable in increasing seed yield of canola than cMAP. However, both the high rate of MAP and cMAP increased seed yield relative to the control at six site years (Table 2.5a, b, c).

Although P availability from APP and MAP is generally considered to be equal (Chien et al. 2011), the inconsistent differences in seed yield response for these two forms of P at the various sites may be due to minor differences in plant stand or biomass accumulation which occurred earlier in the growing season. Both the low and the high rates of APP increased seed yield relative to the control at Lethbridge in 2010; whereas for MAP, only the low rate increased seed yield at this site year (Table 2.5b). However, Lethbridge 2010 was the only site year where APP was superior to MAP. At Brandon in 2012, the low rate of MAP produced significantly greater seed yield than the low rate of APP; at Brandon in 2010, the low rate of MAP increased seed yield relative to the control while the low rate of APP did not (Table 2.5a). The low rate of APP had less biomass (not significant) (Table 2.4a) than the low rate of MAP at these site years, which may have been due to seedling toxicity with APP. When comparing APP and MAP at the high rate, the high rate of MAP increased seed yield relative to the control while the high rate of APP did not at Brandon in 2012 and Kelburn in 2011, while the opposite occurred at Lethbridge in 2010 (Table 2.5a, b). Once again, this may have occurred due to sub-lethal seedling toxicity problems with APP. It is unclear why APP performed better than MAP at Lethbridge in 2010, but may be due to superior physical or chemical availability of this form of P at this site.

2.4.3.2 Sulphur Applied Alone. Low and/or high rates of AS increased seed yield relative to the control at seven site years (Table 2.5a, b, c). However, increasing the rate of AS was not always beneficial. Seed-placed AS applied at 20 kg S ha^{-1} can reduce canola seed yields even at S-responsive sites because of severe reductions in plant stand (Grant et al. 2004). The low rate of AS had significantly greater seed yields than the high rate of AS at Normandin in 2011 (Table 2.5c), although plant stand and biomass accumulation were similar for these two treatments. Similarly, the low rate of AS increased seed yield relative to the control while the high rate did not at Kelburn in 2011 (Table 2.5b). However, the opposite occurred at Normandin in 2010, where there was a response to the additional AS (Table 2.5c), even though there was a significant reduction in plant stand earlier in the growing season. Because the high rate of AS did not reduce plant stand below the optimum range, the nutritional benefit from additional S contributed to further increases in seed yield.

Although ATS and AS both provide reliable sources of plant available SO_4^{2-}-S to increase seed yield of canola in the year of application (Grant et al. 2004), AS was generally superior to ATS. At Brandon in 2010, both the low and high rate of AS increased seed yield relative to the control while ATS did not (Table 2.5a, b). At Kelburn in 2011, the low rate of AS increased seed yield relative to the control while the low rate of ATS did not (Table 2.5b). Plant stand was similar for equivalent rates of AS and ATS at these sites (Table 2.3a, b). In addition, at Lethbridge in 2010, the low rate of AS had significantly greater seed yields than the low rate of ATS (Table 2.5b), which was reflected in the significantly higher biomass accumulation (Table 2.4b). In cold soils, oxidation of $S_2O_3^{2-}$ is slow (Goos and Johnson 2001a) and perhaps the slower availability of SO_4^{2-} from ATS in cold soils could have reduced the early season growth and development, reducing the yield potential of the crop.

2.4.3.3 Phosphorus and Sulphur Blends. Phosphorus and S blends generally increased yields relative to the control more frequently than P or S applied alone. Although the increased yield may have resulted from a nutrient response to both P and S, applying these nutrients together in the same band may also improve P availability and uptake.

The maximum recommended rate for seed-placed MAP may be yield limiting when blended with AS. Increasing from the low to high rate of MAP with low AS significantly increased seed yield at Lethbridge in 2010 (Table 2.5b). Similarly, increasing from the low to high rate of cMAP with low AS significantly increased seed yield at Normandin in 2011 and 2012 and increasing the rate of cMAP with high AS significantly increased seed yield at Lethbridge in 2010 and Normandin in 2011 (Table 2.5b, c). This indicates that 20 kg P_2O_5 ha^{-1} of cMAP was often yield limiting and the higher rate of cMAP was required to reach yield potential. However, increasing the rate of MAP with high AS significantly decreased seed yield at Thunder Bay in 2010 (Table 2.5c). In addition, low cMAP/high AS increased seed yield relative to the control while high cMAP/high AS did not at Kelburn in 2011 and Thunder Bay in 2010 (Table 2.5b, c); however this lack of response to high rates of cMAP with AS was not due to reductions in plant stand at the higher rate, so it is unclear why this occurred.

The cMAP/AS blends may not have provided P at a sufficient rate for crop demand at Thunder Bay in 2010. At this site, the low MAP/AS and high MAP/low AS blends had significantly greater seed yield than equivalent rates of cMAP/AS (Table 2.5c). In addition, the high MAP/high AS blend increased seed yield relative to the control while the high cMAP/high AS blend did not. Because plant stands for most of these treatments were similar (Table 2.3c), we can assume that the higher yields with the MAP blends than with cMAP blends was due to superior nutrient availability.

At Lethbridge in 2010, the low cMAP/low AS blend increased seed yield relative to the control while the low MAP/low AS blend did not (Table 2.5b). Conversely, the low MAP/high AS blend increased seed yield relative to the control while the low cMAP/high AS blend did not (Table 2.5b). These conflicting results may be due to environmental constraints at this site year. The low seed yields and high variability at this site year may have resulted in differences that were difficult to explain.

Increasing from the low to high rate of AS did not have any positive effect on seed yield when blended with the high rate of MAP or cMAP. The high rate of AS with high MAP significantly reduced seed yield compared to the high MAP/low AS blend at Thunder Bay in 2010 (Table 2.5c). Similarly, the high cMAP/low AS blend increased seed yield relative to the control but the high cMAP/high AS blend did not at Kelburn in 2011 and at Thunder Bay in 2010 (Table 2.5b, c). There was, however, a nutrient response to additional AS when AS was blended with the low rate of P fertilizer. At Lethbridge in 2010, the low MAP/high AS blend increased seed yield relative to the control while the low MAP/low AS blend did not (Table 2.5b). Similarly, at Thunder Bay in 2010, the low cMAP/high AS blend increased seed yield while the low cMAP/low AS blend did not (Table 2.5c). There were no significant differences in plant stand or biomass accumulation that could explain the decrease in seed yield at Thunder Bay in 2010 with the higher rates of AS. However, perhaps there were some sub-lethal effects, which could have delayed emergence, growth and development and reduced the capacity of the crop to utilize the additional S, even at S responsive sites.

The frequency of seed yield response was the same for equivalent rates of MES15 and MAP/AS blends (significant response at eight site years for both the low and high rates) (Table 2.5a, b, c). Although half of the S in the MES15 is in the elemental form, the SO_4^{2-}-S supplied by MES15 and soil reserves may have been sufficient to meet crop demand. Also any nutritional benefits from the larger supply of plant available S from the MAP/AS blend may have been offset by seedling toxicity.

The high rate of MES15 was generally superior to the low rate of MES15. Increasing from the low to high rate of MES15 significantly increased seed yield at Kelburn in 2011 and Normandin in 2011 and 2012 (Table 2.5b, c). This was likely due to a response to increased S availability and not an increase in available P because the high MAP/low AS did not increase yields compared to the low MAP/low AS treatment at these sites. Although there was no significant difference in seed yield between equivalent rates of MAP/AS and MES15 at Normandin, the high rate of MES15 was required to reach yield potential at these sites (Table 2.5c), perhaps due to inadequate amounts of plant available S supplied with the low MES15 treatment. The low MAP/low AS blend yielded significantly more than the low MES15 at Kelburn in 2011, perhaps due to inadequate plant available S from the MES15 (Table 2.5b). Seed yields could be lower with MES15 because only the SO_4^{2-}-S portion is considered to be available in the year of application; in previous experiments in Manitoba, the ES in the MES15 was not oxidized at a sufficient rate to be utilized by the crop in any appreciable amount (Kroeker 2005).

Conversely, there was a significant decrease in seed yield with increasing the MES15 rate at Thunder Bay in 2010 (Table 2.5c). However, the high rate of MES15 increased seed yield relative to the control while the high MAP/high AS blend did not (Table 2.5c). There were also differences between MAP/AS blends and MES15 at Lethbridge in 2010. The low MES15 increased seed yield relative to the control while the low MAP/low AS blend did not, but the opposite occurred at the high rate (Table 2.5b). The reason for this variability in performance of the low versus the high rate of MES15 and the performance of MES15 versus MAP/AS blends at these site years is not known.

The high MAP/high Vitasul blend increased seed yields more frequently than high MAP applied alone, indicating that some of the ES in Vitasul may have been oxidized and contributed to the yield response. Vitasul is completely reliant on microbial oxidation to be converted into plant available SO_4^{2-} and is theoretically formulated to disperse into small particles upon wetting in the soil, increasing the surface area for microbes to access it. Smaller particles will generally increase SO_4^{2-}-S release rates (Janzen and Bettany, 1986). There was a significant increase in seed yield with high MAP/high Vitasul compared to high MAP applied alone at Brandon 2010 (Table 2.5a); high MAP/high Vitasul also increased seed yield relative to the control while the high rate of MAP applied alone did not at Lethbridge in 2010 (Table 2.5b). However, the high MAP/high Vitasul blend did not perform better than any of the high MAP/AS blends. In fact, the high MAP/Vitasul blend yielded significantly less than the high MAP/high AS blend at Thunder Bay in 2012 and the high MAP/low AS blend at Thunder Bay in 2010 (Table 2.5c). This indicates that S applied in an immediately available form, such as AS, is the most reliable way to reducing the risk of S deficiency in the year of application (Grant et al. 2004), especially if the S fertilizer is placed with the seed. Furthermore, ES is generally not recommended to be seed-placed (Grant et al. 2012) because ES forms a hydrophobic band, restricting microbial oxidation (Janzen and Bettany 1986).

Generally, MAP/AS blends increased yields more frequently than equivalent rates of APP/ATS, sometimes due to greater plant stand and biomass accumulation earlier in the growing season, indicating that conventional granular fertilizer blends may be less toxic and more available than liquid fertilizer blends. The low MAP/low AS increased seed yield relative to the control while the low APP/low ATS did not at Brandon in 2010 and 2012 and at Kelburn in 2011 (Table 2.5a, b). Similarly at Kelburn in 2011, the low MAP/high AS increased seed yield relative to the control while the low APP/high ATS did not (Table 2.5b). In addition high MAP/high AS also increased seed yield relative to the control but high APP/high ATS did not (Table 2.3b). At Brandon in 2010, high MAP/low AS increased seed yield relative to the control but high APP/low ATS did not (Table 2.5a). The only occurrence where APP/ATS performed better than the MAP/AS was at Lethbridge in 2010 where the high APP/low ATS blend had significantly greater seed yield than the high MAP/low AS blend (Table 2.5b).

These differences between conventional P and S blends are consistent with the P and S sources applied alone. Ammonium sulphate may be superior to ATS due to greater availability, especially early in the growing season when oxidation of $S_2O_3^{2-}$ may be slow in cold soils. In addition, the inconsistent response to P source varied by site year; Lethbridge 2010 was the only site year where an APP blend was superior to a MAP blend. Again, this may be due to the greater seedling toxicity from APP compared to MAP at the Brandon and Kelburn sites that may have slowed the emergence and development of the canola, reducing yield potential.

2.4.4 Overall relationship between seed yield and plant stand

The relationship between mean seed yield and plant stand by fertilizer treatment was significant and inverse when for the granular treatments averaged across all site years (Figure 2.1) and for both granular and liquid fertilizer treatments averaged across all site years with a full treatment set (Figure 2.2). Treatments containing highly available P and S sources, such as MAP and AS, generally had lower mean plant stands than those with novel fertilizers. However, MAP/AS treatments generally produced the highest mean seed yield (Figure 2.1, 2.2) probably because the benefits of the nutritional response outweighed the negative effects of seedling toxicity. The control treatment had a very low seed yield and when removed from the analysis, the relationship between mean plant stand and seed yield for treatments averaged over all site years with a full treatment set was not significant. This could mean that the control treatment was driving the relationship in Figure 2.2. However, when the control treatment was removed from the granular treatment set (Figure 2.1), the inverse relationship remained significant (r^2 = 0.4201, P = 0.0063)

The relationship between plant stand and seed yield as affected by various sources and rates of seed-placed P and S fertilizers also varied by individual site year (Appendix C, Table C.1). Also, although reductions in plant stand can decrease seed yields, the overall mean plant stand for our experiment was well above the critical threshold of 40 plants m^{-2} recommended by the Canola Council of Canada (2011b). As previously mentioned, the seeding rate used in this study was near the high end of the range of recommended seeding rates (Canola Council of Canada, 2011b). If a lower seeding rate had been used, treatments with highly available P and S fertilizers may have reduced the plant stand below the critical threshold, thus reducing yield potential and nutrient response.

Comparing individual treatments, the plant stand and seed yield response varied with fertilizer source and rate. Applying both P and S in the seed-row increased the seed yield compared to either P or S applied alone, but the P and S blends decreased the plant stand (Figure 2.1, 2.2). Comparing equivalent rates of MAP/AS to novel fertilizers, the MAP/AS generally resulted in more seed yield despite causing more seedling toxicity (Figure 2.1). The APP/ATS treatments also had lower plant stands than novel fertilizers; however, the plant stands and seed yield for APP/ATS treatments were generally lower than for equivalent rates of MAP/AS (Figure 2.2). Although applying highly available sources of P and S fertilizer (MAP and/or AS) in the seed-row increases the risk of

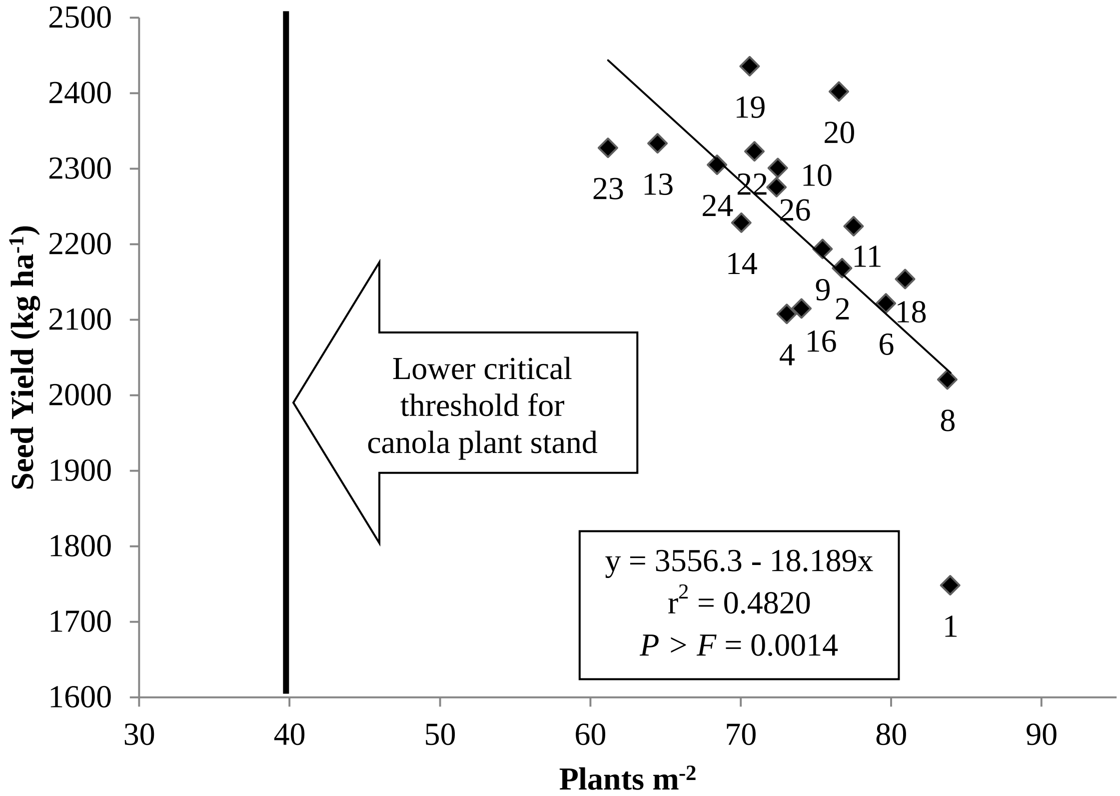

Fig. 2.1 Overall relationship between plant stand and yield as affected by granular seed-placed P and S treatment means for all site years, relative to the minimum threshold of 40 plants m^{-2} recommended for canola. Data points are indicated by treatment numbers for the experiment (listed in Materials and Methods, section 2.3)

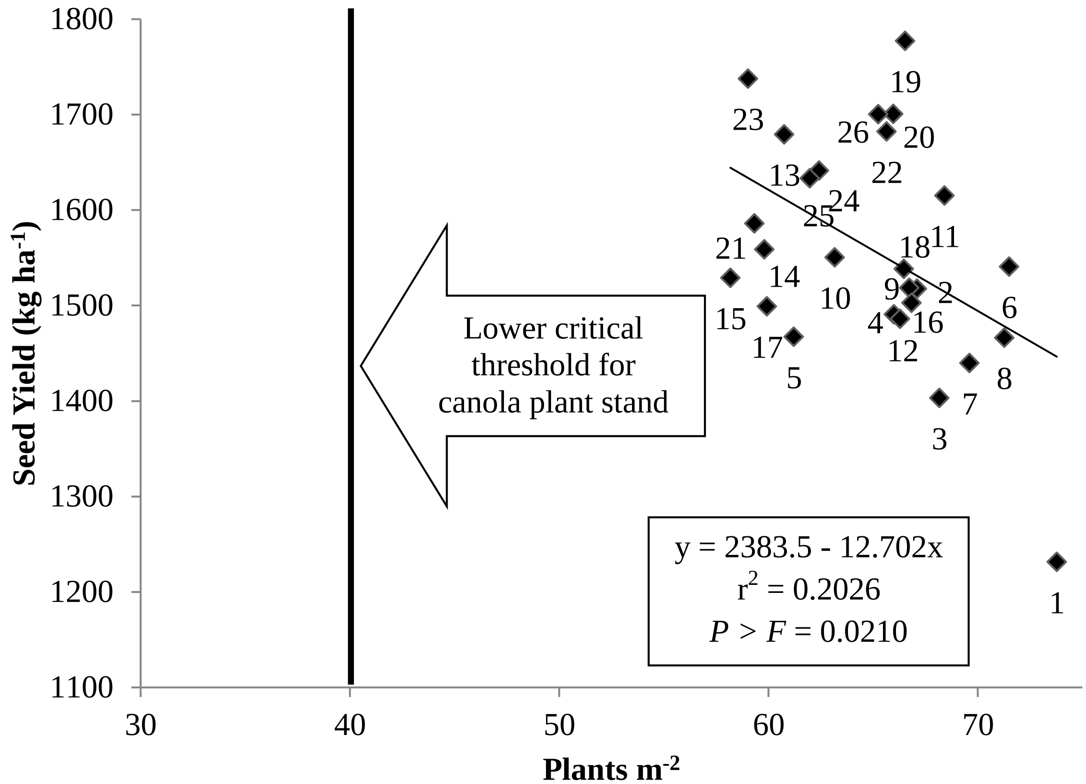

Fig. 2.2 Overall relationship between plant stand and yield as affected by granular and liquid seed-placed P and S treatment means for all site years with a complete set of treatments, relative to the minimum threshold of 40 plants m^{-2} recommended for canola. Data points are indicated by treatment numbers for the experiment (listed in Materials and Methods, section 2.3)

seedling toxicity, these sources can produce a larger nutrient response compared to novel fertilizers if the plant stand is within the optimum range.

2.5 Conclusion

The relationship between canola plant stand and seed yield is variable and reaching yield potential depends on balancing optimum plant stand with adequate rates and suitable placement of plant available P and S. There was no negative impact of P and S fertilizers on seed yield relative to the control; however, source and rate of fertilizer influenced the yield response and the response varied by site year. Seed-placed blends of P and S generally reduced plant stand more frequently than P or S applied alone; however, P and S blends increased seed yield more frequently than P or S applied alone indicating that providing available sources P and S at the time of seeding is beneficial overall. Increasing the rate of MAP alone or in a blend generally had no negative impact on plant stand or seed yield. In fact, the maximum recommended rate for seed-placed MAP may be yield limiting. Although cMAP reduced the salt toxicity of MAP, it may not be as effective as uncoated MAP for supplying P to satisfy nutrient requirements for canola during the entire growing season and higher rates may be required. Increasing the rate of seed-placed AS from 9 to 18 kg S ha^{-1} applied alone or as a blend with P fertilizer can cause reductions in plant stand, which may reduce the capacity of the crop to reach yield potential. Limiting the rate of seed-placed AS applied alone or in a blend may be necessary to maximize yield potential. Seed-placed MES15 and Vitasul are less toxic than equivalent MAP/AS blends because they contain elemental forms of S. These novel fertilizers may be as effective as seed-placed AS in the year of application if S deficiencies are not severe; however, the ES in these sources requires microbial oxidation for be converted to SO_4^{-2}. Liquid P and S fertilizers were generally more toxic and less effective in increasing seed yield as compared to granular fertilizers.

To maximize the benefits and minimize the risks of applying MAP and AS, farmers with single shoot, low SBU seeding equipment, should reserve the limited tolerance of canola for seed-row fertilizer for MAP. Unlike P, S is relatively mobile in the soil and could be placed away from the seed with substantially less risk of toxicity and no loss in agronomic efficiency. If P and S blends are placed in the seed-row, it may be necessary to use higher seeding rates to adjust for the lower plant stand due to seedling toxicity and maintain an acceptable plant density. Further research is required to identify the response of canola at different planting densities, including low seeding rates, to various P and S blends. Research could also be done to analyze the sub-lethal impacts of various sources and rates of seed-placed P and S fertilizer on canola emergence, growth and development throughout the growing season.

3. CANOLA SEEDLING DAMAGE FROM SEED-PLACED MONOAMMONIUM PHOSPHATE AND AMMONIUM SULPHATE APPLIED ON SOILS FROM DIFFERENT LANDSCAPE POSITIONS

Key Words: Monoammonium phosphate, ammonium sulphate, seed-placed fertilizer, canola (*Brassica napus*), calcium carbonate content, ammonia and salt toxicity

3.1 Abstract

Monoammonium phosphate (MAP) and ammonium sulphate (AS) fertilizers differ in their risk of ammonia and salt toxicity and can significantly reduce canola plant stands if applied in the seed-row above recommended safe rates. The risk of ammonia (NH_3) toxicity from AS may be especially severe on soils with a high calcium carbonate ($CaCO_3$) content, which can frequently occur on eroded hilltops in Canadian Prairie landscapes. A growth room experiment was conducted to determine the effect of soils from different landscape positions on the toxicity of seed-placed MAP and AS with canola. Soils were collected from hilltops and depressions in fields near Nesbitt and Minnedosa, MB. Under controlled environment conditions, canola emergence was reduced and delayed by seed-placed MAP and AS fertilizers applied alone and as a blend. Reduced and delayed emergence were especially severe on the soil from the hilltop soils where $CaCO_3$ content was greater and soil water content was lower than for the soils from depressions. Applied at recommended rates, AS has a greater potential to reduce plant stands than MAP because it has a higher salt index but also has a greater risk of NH_3

toxicity on calcareous soils. Whenever possible, AS should be placed away from the seed, reserving canola's limited tolerance for seed-row fertilizer for phosphorus (P) fertilizer.

3.2 Introduction

Phosphorus and sulphur (S) fertilizers are commonly blended and placed in the seed-row with canola as farmers are adopting one-pass seeding systems. This practice is regarded as the most efficient placement for P because plant available HPO_4^{2-} and $H_2PO_4^-$ are relatively immobile in the soil and are taken up by the plant mostly by diffusion (Grant 2001). In Canada, under wet or cool conditions in spring when P diffusion and root growth are typically limited, a small amount of P, "starter P", applied in the seed-row will often result in an early season growth response (Grant et al. 2001). In alkaline or calcareous soils typically found in the Canadian Prairies, MAP is, by far, the most common P source used in canola crop production. The saturated solution of MAP is acidic so it has a relatively low potential to form ammonia and remains soluble (Hedley and McLaughlin 2005).

Unlike P, plant available sulphate (SO_4^{2-})-S is mobile in the soil, so placement and timing options are more flexible (Grant et al. 2012). However, applying S fertilizer while seeding is usually the most practical and effective time of application (Malhi and Gill 2002) and spring application can also reduce the risk of S-deficiency later in the growing season by avoiding losses due to leaching of fall-applied S on coarse textured soils (Malhi 2005). Ammonium sulphate is a common granular S source used in canola crop production because it provides a reliable, fully available source of plant available SO_4^{2-}-S in the year of application (Grant et al. 2003, 2004).

Although seed-placement of P and S fertilizers are convenient and efficient, canola is relatively sensitive to seed-placed fertilizer compared to cereal crops (Nyborg 1961). Emergence can be reduced and delayed with rates applied necessary to satisfy canola crop requirements (Nyborg 1961). With typical seeding equipment (15% seed-bed utilization (SBU)), safe rates are generally limited to approximately 22 kg P_2O_5 ha^{-1} as MAP or 11 kg S ha^{-1} as AS with medium to fine-textured soils and good moisture conditions (MAFRI 2007). However, SBU will affect the concentration of salts in the seed-row and thus wider row spacing or narrower opener widths will decrease the rates of fertilizer that can be safely applied (Nyborg and Hennig 1959).

Fertilizer sources can also differ in toxicity. The salt index can be used to estimate the potential seedling damage caused by the effect of a fertilizer on the osmotic potential in the soil solution. For example, MAP has a much lower salt index (29.9) than AS (69.0), so the potential for crop injury is much greater for AS (Radar et al. 1943). The potential to form NH_3 is also different for these two fertilizers. In neutral to acid soil, MAP and AS applied in a band will both have a low potential to form NH_3 because their saturated solution pHs are acidic (MAP 4.7 and AS 4.5) (Dowling 1988); however, in calcareous soil, AS can react with $CaCO_3$ to form NH_3. Ammonium sulphate reacts with the $CaCO_3$ in the soil, forming ammonium carbonate ($(NH_4)_2CO_3$), and calcium sulphate ($CaSO_4$)(Eq. 1). The $CaSO_4$ precipitates, which drives the reaction to the right (Eq. 2). The $(NH_4)_2CO_3$ spontaneously decomposes, releasing NH_3 and carbon dioxide (Eq. 3), decreasing the pH of the surrounding soil (Fenn and Kissel 1973).

$$(NH_4)_2SO_4 + CaCO_3 \leftrightarrow (NH_4)_2CO_3 + CaSO_4 \quad (1)$$

$$(NH_4)_2CO_3 + H_2O \leftrightarrow 2NH_3\uparrow + H_2O + CO_2\uparrow \leftrightarrow 2NH_4OH \quad (2)$$

$$NH_4^+ + OH^- \leftrightarrow NH_4OH \leftrightarrow NH_3\uparrow + H_2O \quad (3)$$

Potential injury to seedlings can be managed using the appropriate source, rate and seedbed utilization. Soil properties can also affect the toxicity of fertilizers; therefore, a uniform fertilizer application can behave differently in areas of the field with variable soil properties. For example, areas of a field with high soil $CaCO_3$ content or high pH will have more risk of NH_3 formation and toxicity than other areas because of the reactions mentioned earlier (Fenn and Kissel 1973). Also, differences in soil texture across the landscape may result in differences in buffering capacity, cation exchange capacity (CEC) and soil moisture holding capacity. Soil moisture will affect the salt stress cause by fertilizer. Decreasing the soil moisture content will decrease the dilution of fertilizer salts and increase the osmotic pressure of the soil solution, increasing the risk of seedling damage (Olson and Dreier 1956, Nyborg and Hennig 1969). Water content of the soil will also affect NH_3 formation from AS in calcareous soils. As the water content decreases, the precipitation of $CaSO_4$ increases, driving Eq. 1 to the right (Fenn and Kissel 1973).

Erosion in hummocky landscapes can expose calcareous sub-soil, which increases the variability in soil properties within a field. The risk of NH_3 toxicity may be especially severe on soils with a high $CaCO_3$ content, which can frequently occur on eroded hilltops in Canadian Prairie landscapes. The objective of this study was to determine if soils from different landscape positions affected the toxicity of AS and MAP fertilizers placed in the seed-row with canola under controlled environment conditions.

3.3 Materials and Methods

3.3.1 Experimental Design and Treatments

The surface soil (0-15 cm) from two sites, Minnedosa, MB (SW 29-7-18 W1) and Nesbitt, MB (NE 34-16-19 W1) was collected in the spring of 2012. Soil was collected from two distinct areas of each field: one area with visible erosion on the hilltop position in the landscape and another area from a nearby depressional area. The fertilizer treatments applied to each soil consisted of a full factorial combination of three rates of seed-placed MAP and AS. Soil and fertilizer treatments were arranged in a randomized complete block design, with four replicates. Rates of MAP applied were 0, 20 (Low) or 40 kg P_2O_5 ha^{-1} (High) and rates of S applied were 0, 9 (Low) or 18 kg S ha^{-1} (High). The following treatments were placed in the seed-row:

1) Control
2) Low AS
3) High AS
4) Low MAP
5) Low MAP/Low AS
6) Low MAP/High AS
7) High MAP
8) High MAP/Low AS
9) High MAP/High AS

The fertilizer and seed were applied in a 2.5 cm band assuming a row spacing of 20.32 cm to mimic the seedbed utilization of the seeding equipment used in the field study (Chapter 2). No additional fertilizer was added and nitrogen rates were not balanced, because of the short duration of the experiment. The canola cultivar used was InVigor 5440 and the canola was planted at a depth of 1.9 cm by layering the soil in each pot.

3.3.2 Site Characteristics

Soils were characterised by analyzing a composite soil sample from the soil collected from each landscape position at each site for organic matter (loss on ignition method), soluble salts (1:1 soil to water), texture (USDA texture by hydrometer), CEC (sum of the exchangeable cations) $CaCO_3$ content (Modified Williams method), and Olsen P (sodium bicarbonate method) at AGVISE Laboratories, Northwood, ND.

3.3.3 Soil Preparation, Planting and Monitoring of Emergence

Each soil was air dried and passed through a 0.8 cm sieve. Container capacity was used to determine a suitable soil water content instead of a field capacity method because the field capacity method is not representative of the controlled conditions conducted in this pot study. Container capacity for soil from each landscape position was determined separately. First, the volume of the pot was calculated to depth of 10 cm. A pot was filled and packed lightly to a depth of 10 cm and weighed to determine bulk density. The same soil was then used to fill pill bottles using the same bulk density to a depth of 7 cm. A range of gravimetric water contents increasing at 1% intervals were applied to the pill bottles using deionised water. After six hours, the pill bottle where the lowest water content that had allowed the water front to reach the bottom of the container was chosen to represent container capacity. The entire pill bottle was emptied, soil was mixed and approximately 25 g subsample was extracted to determine the gravimetric water of the soil for that particular bottle of soil. The subsample was weighed wet, dried at 105°C for 24 hours and weighed dry to determine gravimetric water content.

To prepare the soil before seeding, air dried soil was thoroughly mixed and pots were filled to a base depth of 8.1 cm. Four composite subsamples were taken from each soil to measure the gravimetric water content of the air-dried soil. Water was added to this base layer of soil to bring the gravimetric moisture content to the container capacity determined earlier. Pots were sealed and the moisture front was allowed to move to the bottom and the moisture content to equilibrate for at least 24 hours.

Two rows of canola were seeded 15.2 cm apart in each pot. Within each row, ten canola seeds were seeded 2.1 cm apart. The seeding rate in the pots would be equivalent to 215 seeds m^{-2} in the field. Fertilizer treatments were added in a 2.5 cm band within each the seed-row. After seeding and fertilizing, the top layer of soil (1.9 cm) was added to bring the total depth of soil to 10 cm. The top layer was then watered to reach container capacity and the lids were placed loosely on the pots, without sealing, to reduce evaporation losses. The growth chamber was set to a humidity of 60%, daytime temperature 25°C, night-time temperature 16°C and a 16 hour photoperiod.

Lids remained on the pots until the date of emergence. Date of emergence was recorded when at least half of the seedlings had emerged from the control treatments on the soil collected from the depression. Plant stand was assessed every two days until four weeks after emergence. Soil water content was then monitored every two days after the lids were removed or watering occurred. All pots were watered and brought back to 100% container capacity when soil water was reduced to below 70% of container capacity. Pots were re-randomized in the growth chamber each time they were watered.

3.3.4 Statistical Analysis

The Mixed Procedure in SAS 9.3 was used to conduct statistical analysis for the growth chamber experiment (SAS Institute, Inc. 2013). A 3-way complete factorial, repeated measures ANOVA was used to test the significance of the fixed effects (MAP rate, AS rate and landscape positions) over a period of repeated sampling dates, which consisted of observations ever two days after emergence for four weeks. Each site was analyzed as a separate dataset. A first order autoregressive variance-covariance structure with heterogeneous variance across periods (ARH(1)) was used. Assumptions regarding the conformity of the data were tested using Proc Univariate. Each dataset was tested for normality using the Shapiro-Wilk Statistic; since both datasets followed a normal distribution, transformations were not required. Model effects were considered significant at $P < 0.05$. Means were separated using a SAS macro (pdmix800) and adjusted using the Tukey Method. Means were considered different at $P < 0.05$.

3.4 Results and Discussion

3.4.1 Site Characteristics

Soils collected from the Minnedosa site were from the Erickson Series (Table 3.1). The soil collected from the hilltop position at this site was moderately calcareous. This soil

Table 3.1 Characteristics of soils collected from Minnedosa and Nesbitt, MB sites

	Minnedosa		Nesbitt	
	Depression	Hilltop	Depression	Hilltop
UTM coordinates	14U 0428486 5584999	14U 0428493 5584553	14U 436153 5493720	14U 436163 5493772
Soil Series	Erickson	Erickson	Hilton	Hilton
Texture	SCL	CL	SL	L
pH	7.2	7.8	7.7	7.9
OM (%)	9	3.2	6	1.8
CEC (meq)	29.7	32	26.3	28.2
Sol. Salts (mmho/cm)	0.9	0.5	1.1	0.6
Carbonate (%)	0.4	8.4	0.5	21
Container Capacity (%)^z	39.8	33.1	25.8	17.2
Olsen P (mg kg^{-1})	47	13	23	30

^{z} Gravimetric water content

had a higher pH and $CaCO_3$ content and lower organic matter content and moisture holding capacity than the soil collected from the depression position. Soils collected from the Nesbitt site were from the Hilton Series (Table 3.1). The soil from the hilltop position at this site was characteristic of the calcareous sub-soil of this series, evidently where erosion had exposed the sub-soil. Again, this soil had a higher pH and $CaCO_3$ content and lower organic matter content and moisture holding capacity than the soil collected from the depression position.

3.4.2 Plant stand

Plant stand was assessed after at least 50% of the seedling had emerged in the control treatment on the soil from the depression. However, there may have been differences in emergence prior to the commencement of sampling that may not have been detected because of this delay in plant stand assessment.

Starter P can also increase early season seedling growth in cool soils, when soil P diffusion and root growth are limited, by providing an immediately available source of P in a favourable position for uptake (Grant et al. 2001). We did not suspect the P fertilizer treatments improved seedling vigor because soil P in all soils were not likely limiting growth under the controlled environment conditions. The temperatures in the growth chamber are relatively warm compared to temperatures that may occur in the field at the time of seeding, so diffusion of soil P is not limited. In addition, soil test P levels in all soils were relatively high.

3.4.2.1 Minnedosa Site. There were significant main effects of MAP rate, AS rate, soils from different landscape positions and days after emergence on the plant stand of canola

Table 3.2 ANOVA for the effect of soil from different landscape positions, MAP rate, AS rate and days after emergence on canola seedling emergence in soil collected from Minnedosa and Nesbitt, MB

	Minnedosa		Nesbitt	
Model Effect	df	*F*-value	df	*F*-value
MAP rate	2	32.4***	2	99.7***
AS rate	2	3.9*	2	73.4***
Landscape position (LP)	1	29.1***	1	156.2***
Days after emergence (DAE)	13	13.1***	14	32.4***
MAP rate*DAE	26	1.6*	28	1.9**
AS rate*DAE	26	1.5NS	28	1.2NS
MAP rate*AS rate	4	1.7NS	4	3.4*
LP*MAP rate	2	2.6NS	2	9.6**
LP*AS rate	2	5.2**	2	21.5***
LP*DAE	13	1.6NS	14	2.8**
LP*MAP rate*AS rate	4	0.7NS	4	3.1*
MAP rate*AS rate*DAE	52	0.9NS	56	1.3NS
LP*MAP rate*DAE	26	0.9NS	28	1.8**
LP*AS rate*DAE	26	0.9NS	28	1.3NS
LP*MAP rate*AS rate*DAE	52	0.9NS	56	1.5*

* Indicates that the model effect was significant (P < 0.05); ** Indicates that the model effect was significant (P < 0.01); *** Indicates that the model effect was significant (P < 0.001); NS indicates that the model effect was not significant (P >0.05)

in soil from the Minnedosa site. There was also a significant interaction between AS rate and landscape position (Figure 3.1). Ammonium sulphate rate did not affect emergence on the soil from the depression; however, emergence was reduced as AS rate increased on the soil from the hilltop. This was probably caused by a greater concentration of NH_3 in the fertilizer band due to a reaction between the AS and $CaCO_3$ (Eq. 1 - Eq. 3). The $CaCO_3$ content of the soil from the hilltop was greater (8.4%) than the soil from the depression (0.4%); therefore, the soil from the hilltop had a greater capacity to form NH_3 with AS than the soil from the depression. Results from Fenn and Kissel (1975) showed that there was a large increase in NH_3 volatilization occurred with an increase in $CaCO_3$ content as small as from 0.5% to 1.3%. Although a lower water holding capacity and CEC and greater pH can also increase NH_3 toxicity, the difference in these soil properties between the two soils were not likely not large enough to have caused such a large difference in response to AS. There was also a significant interaction effect of MAP rate and days after emergence on the plant stand of canola on the soils from the Minnedosa site (Figure 3.2). The mean plant stand for treatments containing 40 kg P_2O_5 ha^{-1} of MAP were significantly lower than those that contained either 0 or 20 kg P_2O_5 ha^{-1}. In addition, both the mean plant stand for treatments containing either 0 and 20 kg P_2O_5 ha^{-1} reached 90% of maximum plant stand at 2 days after emergence while the maximum plant stand for 40 kg P_2O_5 ha^{-1} treatments was not reached until 4 days after emergence. In a similar study conducted by Qian et al. (2010), canola emergence was reduced at rates greater than

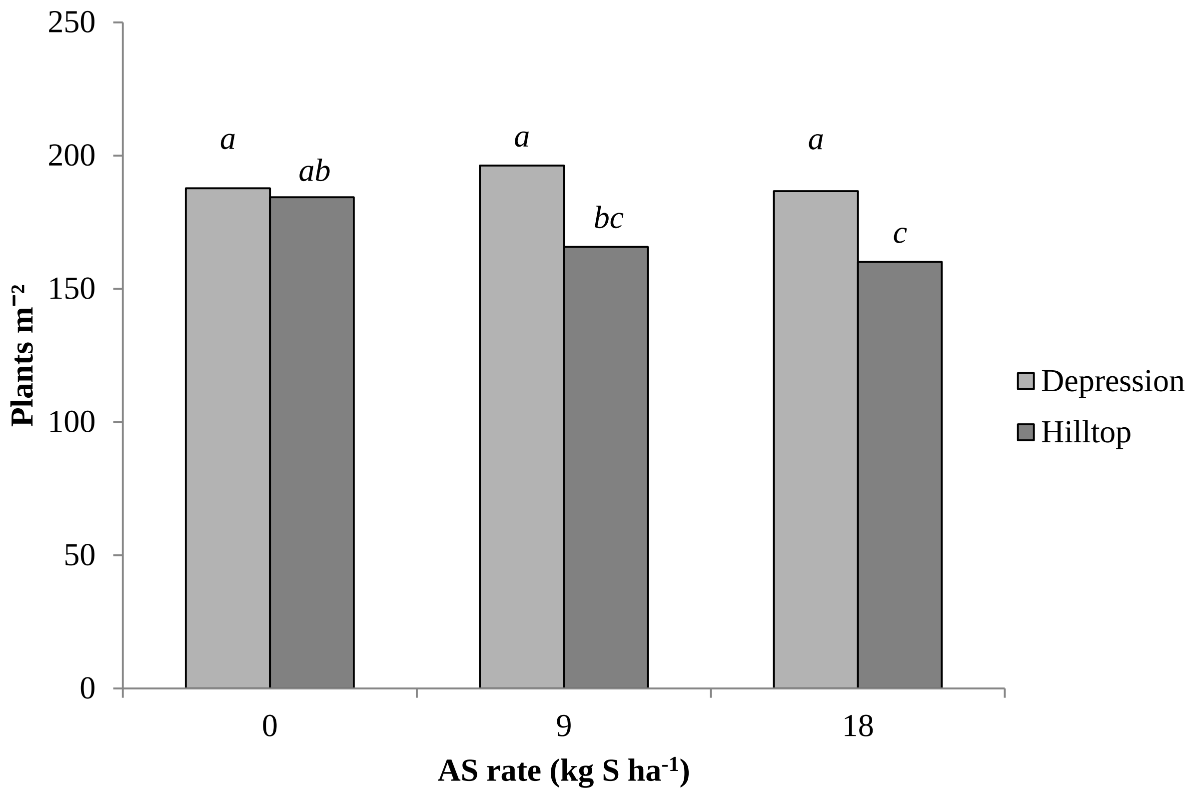

Fig. 3.1 Plant stand means of canola influenced by the interacting effect of AS rate and soils from different landscape position on soil from the Minnedosa, MB site. Plant stands with the same letter grouping are not significantly different at $P < 0.05$

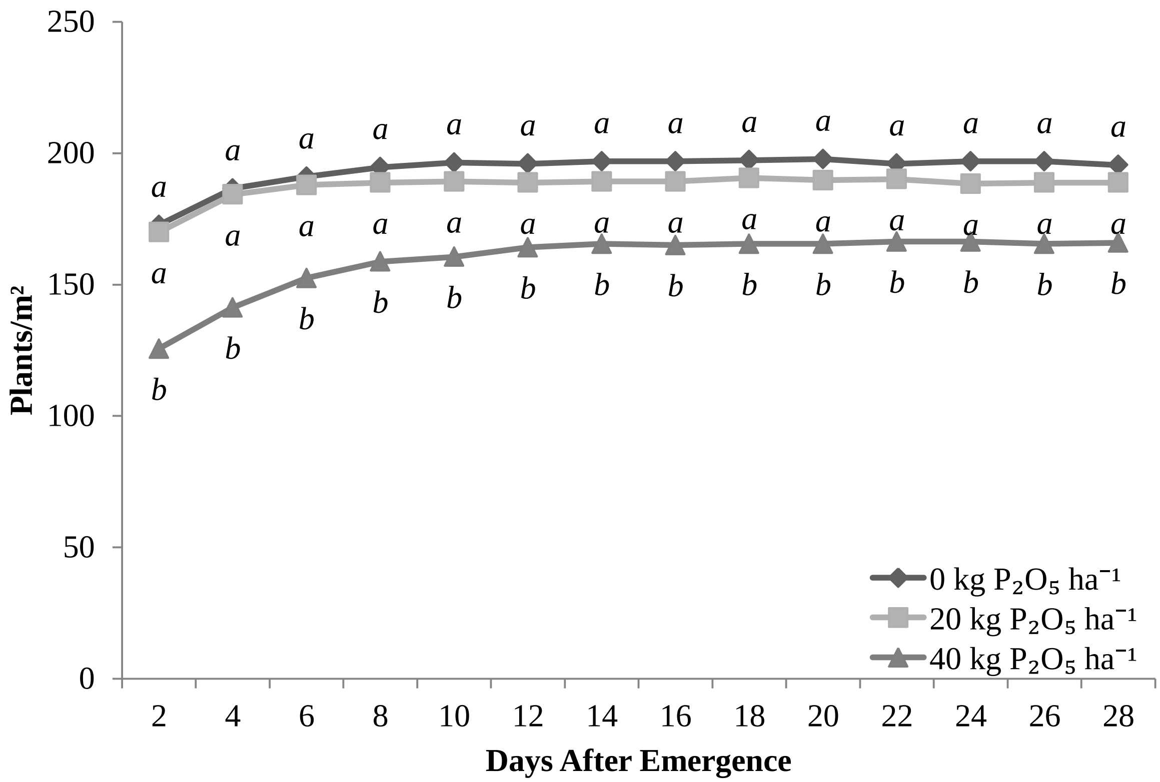

Fig. 3.2 Plant stand means of canola influenced by interacting effect of MAP rate and days after emergence on soil from the Minnedosa, MB site. Within each sampling date, plant stands with the same letter grouping are not significantly different at $P < 0.05$

30 P_2O_5 ha^{-1} of seed-placed MAP. Similarly, Dowling (1996) found that increasing concentrations of osmotic pressure decreased seedling emergence and increased time to emergence of canola.

3.4.2.2 Nesbitt Site. At the Nesbitt site, there was a significant four-way interaction, between MAP rate, AS rate, soils from different landscape positions and days after emergence (Table 3.2). On the soil from the depression, there was no significant difference in plant stand between the control and either rate of AS at any of the sampling dates (Figure 3.3a, b; Appendix D, Table D.4a, b). However, plant emergence was slightly slower for the high AS rate compared to the low AS rate or the control. The plant stand for the control and low rate AS treatments reached 90% of maximum at 0 and 2 days after emergence, respectively, while the high AS treatment did not reach 90% of maximum emergence until 6 days after emergence (Appendix E, Table E.1a).

For the hilltop soil, the total plant stand was lower and the rate of emergence was slower as the rate of AS applied alone increased from the low to high rate. The low rate of AS had significantly lower plant stand than the control for the first two days after emergence (Appendix D, Table D.4a), while the high rate of AS significantly reduced plant stand compared to the control at all sampling dates (Appendix D, Table D.4a, b). In the hilltop soil, emergence for the AS treatments was much slower than for the control treatments. Emergence for the control and low AS treatments reached 90% of maximum emergence at 2 and 10 days after emergence, respectively, while the high AS treatment did not reach 90% of maximum emergence until 20 days after emergence (Appendix E, Table E.1a, b).

The main reason why the effect of AS rate on canola emergence was greater for the hilltop soil than for the depression soil was likely because of the higher $CaCO_3$ content in the hilltop soil. As previously discussed, the $CaCO_3$ content of the soil will affect the formation of NH_3 (Eq. 1 - Eq. 3), and hence the toxicity of AS. Although there was an AS rate by landscape position interaction for the Minnedosa site, the difference in $CaCO_3$ content between landscape positions was much greater for the Nesbitt site (Table 3.1). The lethal and sub-lethal effects of the elevated NH_3 concentration in the soil from the hilltop likely reduced and delayed emergence of the canola. The hilltop soil also had a lower water content compared to the depression soil, which may have caused greater salt toxicity on the hilltop soil.

The effect of landscape position and MAP rate also affected the total plant stand and rate of emergence. On the soil from the depression, there was no significant difference in plant stand between the control and either rate of MAP applied alone at any of the sampling dates (Figure 3.3c, d; Appendix D, Table D.4a, b). However, on the soil from the hilltop, the high MAP treatment significantly reduced plant stand compared to the control and the low MAP treatments at all sampling dates. In addition, seedling emergence was also delayed by the high rate of MAP on the hilltop soils; maximum plant stand was not reached until 14 days after emergence compared to 2 and 4 days after emergence for the control and low MAP treatments, respectively (Appendix E, Table E.1a, b).

The reduction and delay of emergence of canola with MAP on the soil from the hilltop may have been due to the lower water content of the soil relative to the soil from the depression (Table 3.1). The low moisture content may have provided sufficient moisture to solubilise the fertilizer granules, but not enough to dilute the fertilizer salts and thus the fertilizer band would have a greater osmotic pressure. In field experiments conducted by Nyborg and Hennig (1969) emergence was generally reduced as moisture content decreased and canola plant stands were reduced as seed-row MAP rate increased. Similarly, in a growth chamber experiment, Olson and Dreier (1956) observed an inhibitory effect on cereal emergence with 45 kg N ha^{-1} and 34 kg P_2O_5 ha^{-1} seed-placed urea and superphosphate under deficient moisture conditions for as little as four days.

The effect of MAP/AS blends on canola emergence varied by landscape position (Figure 3.3e, f). In the soil from the depression, blending AS with MAP decreased and delayed emergence to a greater extent than MAP applied alone. Applying the high rate of

MAP with either rate of AS resulted in significantly lower plant stands compared to the control over the entire sampling period (Appendix D, Table D.4a, b).

Seedling damage from MAP and AS blends was more severe on the hilltop soil than from MAP or AS applied alone. However, in the hilltop soil, the seedling toxicity appeared to be caused by AS. Over the entire sampling period, the plant stand for the high rate of AS was significantly lower than for the control and never significantly different from the MAP/AS blends which included a high rate of AS (Appendix D, Table D.4a, b). In other words, adding MAP to the high rate of AS did not cause additional seedling damage. As previously discussed, the greater potential of AS to form NH_3 on the hilltop soil likely increased the seedling damage in the treatments containing the high rate of AS.

Conversely, blending MAP with AS may have reduced the seedling toxicity of AS by reducing NH_3 formation on the soil from the hilltop. The low rate of AS resulted in significantly lower plant stands compared to the control at 0-2 days after emergence while the plant stand with the low MAP/low AS treatment was never statistically different from the control (Appendix D, Table D.4a, b). Also, the high AS treatment had significantly lower plant stands than the low MAP/high AS treatment on the soil from the hilltop at 8-12 days after emergence. In addition, the threshold of 90% of maximum plant stand was reached sooner for the low MAP/high AS treatment than for the high AS treatment (10 versus 20 days after emergence, respectively. Although the reaction zone for AS is normally acidic, in calcareous soil the reaction between AS and $CaCO_3$ increases the pH of the soil surrounding the fertilizer, increasing NH_3 formation (Eq. 1-Eq.3). However, MAP is acidic, so adding MAP could have offset the increase in pH caused by the

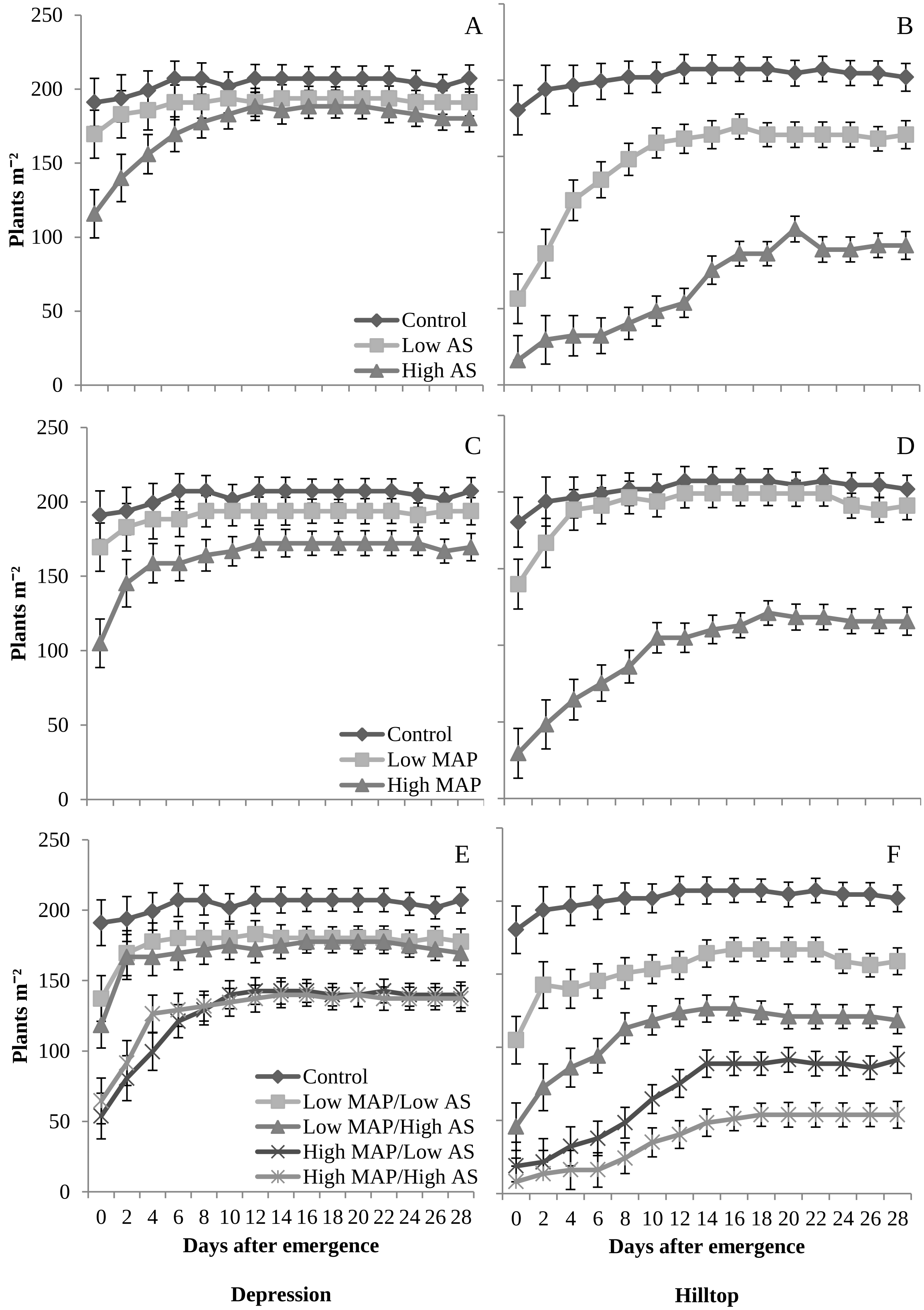

Fig. 3.3 Plant stand means of canola influenced by the interacting effect of landscape position, MAP rate, AS rate and days after emergence on soil from the Nesbitt, MB site. Error bars indicate standard error of the mean at each day after emergence

reaction between AS and $CaCO_3$. Fenn (1975) found that substituting just 30% of AS with MAP decreased the formation of NH_4CO_3 (Eq. 1) which subsequently reduced NH_3 formation compared to that for AS applied alone. However, blending the high rate of MAP with AS did not provide a safening effect; in fact, at the higher rate of MAP, any potential benefits of acidification were probably offset by more osmotic stress.

4.5 Conclusion

Canola emergence was reduced and delayed by seed-placed MAP and AS due to salt and NH_3 toxicity. Soil properties varied by landscape position within each of the two fields, affecting the toxicity of fertilizers. Seed-placed MAP and AS caused plant stand reductions and delayed emergence on soils from both landscape positions; however, the severity was greater on the hilltop soil, especially with high rates of MAP and/or AS. Plant stand reductions from AS were much more severe on hilltop than depression soils, probably because AS reacted with $CaCO_3$ in the hilltop soils, forming NH_3. Applying a low rate of MAP to AS may reduce seedling toxicity on calcareous soil by reducing NH_3 formation. Lower water holding capacity and subsequently higher concentrations of salts in both fertilizers may have also contributed to stand reductions and delayed emergence in the hilltop soils, compared to the depression soils. Delayed emergence of canola due to sub-lethal rates of fertilizer increases the vulnerability of seedlings to environmental stress and decreases the uniformity of crop development and maturity. A reduction in emergence below the optimum threshold could limit yield potential and increase crop competition from weeds. Since blending high rates of MAP with AS can reduce and delay emergence, canola's limited tolerance for seed-row fertilizer should be reserved for MAP. Phosphorus is immobile in the soil and MAP should therefore be placed near the seed. Sulphate-S is mobile in the soil and thus placement options are more flexible for AS.

4. OVERALL SYNTHESIS

Monoammonium phosphate (MAP) and ammonium sulphate (AS) are highly available sources of phosphorus (P) and sulphur (S) which reliably increase nutrient uptake and seed yield of canola. Seed-row placement of MAP and AS is both efficient and convenient but is risky in terms of seedling damage because canola is relatively sensitive to seed-placed fertilizers. Low seedbed utilization (SBU) seeding equipment can increase the concentration of fertilizers in the seed-row, increasing the risk of seedling damage. Therefore, due to equipment limitations, maximum recommended rates of seed-placed P and S are restricted to levels that may be insufficient to meet crop demand. To reduce seedling toxicity and improve nutrient uptake, novel fertilizers such as coated MAP, MicroEssentials S15 and Vitasul have been formulated with the expectation that available nutrients will be slowly released throughout the growing season to match crop demand better than conventional sources. Since farmers apply P and S at the time of seeding and seed-placement is often their only method to do so, they should select the appropriate source and rate that suits their soil properties, climatic conditions and SBU to minimize seeding damage and optimize seed yield.

Fertilizer sources differ in nutrient availability and seedling toxicity. Conventional sources of P and S such as MAP and AS are highly available, but caused significant seedling damage in some instances in both the field (Chapter 2) and growth chamber studies (Chapter 3). In addition, blending MAP and AS caused more seedling damage compared to either MAP or AS applied alone. Under field conditions (Chapter

2), conventional P and S sources reduced plant stand relative to the control more frequently than novel P and S sources. Novel sources were also more effective in increasing early season biomass compared to the conventional sources of P and S, which may be due to sub-lethal effects of fertilizer toxicity on seedlings, delaying emergence and crop development. However, MAP and AS blends increased seed yield more consistently compared to either P or S applied alone or the novel sources. Although often less toxic, the novel sources may not reliably release adequate quantities of available nutrients to match crop demand throughout the growing season. Although the site characteristics and nutrient uptake data were not included in Chapter 2, there was often a yield response from providing an available source of both P and S at the time of seeding. Despite the risk of blending AS in the seed-row with P fertilizers, blending P and S fertilizers may be beneficial in increasing P response. Dual banding S fertilizers with P fertilizers can improve P availability and uptake; however, it is unclear if this occurred in the field study for canola. Future research may compare the response of P and S fertilizers applied separately versus in a dual band to determine if there is an advantage in dual banding P and S for canola.

High rates of P or S had a much greater effect on seedling toxicity in the growth chamber experiment than in the field experiment. Under field conditions (Chapter 2) applying the maximum recommended safe rate of MAP and AS alone or as a blend was low risk in terms of seedling damage. Applying MAP above the recommended safe rate alone or in a blend with AS was also low risk and generally improved seed yield response. However, applying AS above the recommended safe rate alone or as a blend with MAP or cMAP increased seedling damage and was generally not beneficial in terms of increasing seed yield. Applying the high rate of novel sources such as cMAP or

MES15, generally did not increase seedling damage compared to the low rate, but the high rate was often required to improve seed yield response. This indicates that novel sources applied at the low rate may not release sufficient available nutrients to meet crop demand. Under controlled environment conditions (Chapter 3), the plant stand response to MAP and AS applied above the maximum recommended safe rates was dependent on differences in soil properties between landscape positions. On soils from the depression, increasing from the low to high rate of MAP or AS applied alone or as a blend was relatively low risk. The depression soils were likely typical of the soils found in our field study, and thus the responses were similar. However, the reduction and delay in canola emergence with the high rate of MAP and/or AS was much more severe on the soils from the hilltop. Although farmers can select the appropriate rate and sources of P or S to minimize seedling damage, soil properties can also have a large effect on the toxicity of the fertilizers applied.

In both the field and growth chamber studies, soil and moisture conditions affected the toxicity of fertilizers. In the field experiment, treatment responses were highly variable, depending on site and year. The risk of seedling toxicity from seed-placed fertilizer varies with soil characteristics, which, in turn can vary dramatically with locations across Canada (e.g., Lethbridge and Normandin are 3500 km apart) or landscape positions within a field (e.g., hilltop and depression positions were only 50 m apart at Nesbitt). In the growth chamber study, calcareous soils collected from eroded hilltops increased the toxicity of AS compared to non-calcareous soils collected from depressions. The lower soil water content of the soil from the hilltops may also have reduced the dilution of fertilizer salts and increased the seedling damage. Seedling toxicity of AS appeared to be reduced by adding the low rate of MAP to AS on the soil from the hilltops. On highly calcareous soils, adding MAP may reduce the toxicity of AS by reducing the pH of the fertilizer reaction zone and subsequent formation of NH_3. However, increasing the rate of MAP above the maximum recommended safe rate did not provide a safening effect and in fact, contributed to increased seedling toxicity due to higher osmotic stress.

Detailed measurements of seedling emergence are required to capture the full extent of seedling damage from excess seed-row fertilizer. In the growth chamber study, high rates of MAP and AS applied alone or as a blend delayed emergence, especially on calcareous hilltop soils and generally within the first two weeks after emergence. However, the plant stand stabilized in the subsequent two to four weeks of sampling. In the field study, plant stand was assessed at two and four weeks after emergence; therefore, the sampling dates in the field study likely would not have captured any delay in emergence due to seed-placed fertilizers. Earlier and more frequent plant counts are required under field conditions to determine if seed-placed P and S fertilizers delay emergence and if sub-lethal fertilizer toxicity affects crop development, biomass accumulation and seed yield.

Seeding rates may have a substantial impact on the effect of seedling damage on seed yield and crop quality. Although seed-placed P and S fertilizers occasionally reduced plant stands in the field experiment, the plant stands were generally above the critical threshold of 40 plants m^{-2} recommended by the Canola Council of Canada and there was a consistent nutrient response to highly available sources of P and S. However, a relatively high seeding rate was used in this study and a lower seeding rate may result in plant densities below the critical threshold, limiting yield potential, reducing oil quality, delaying maturity and increasing weed competition. Oil quality was assessed in the field study, but was not analyzed in time to be included in the manuscript. Therefore, further research is required to determine canola yield and quality response to seed-placed P and S fertilizer at lower plant densities.

When considering how much seed-row P or S fertilizer to apply with canola, it is important to remember that applying P in the seed-row is the most efficient placement for P fertilizer. Adding S along with P in the seed-row increases the risk of seedling toxicity, which could reduce seed yield of canola where plant stands are otherwise marginally sufficient. However, unlike P, S is mobile in the soil; therefore S fertilizer application is flexible and effective over a variety of different placement and timing options. In a situation where a farmer is limited by a low SBU seeder, P should be placed with the seed and S be placed away from the seed row to minimize seedling toxicity and optimize crop growth and nutrient use efficiency.

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6. APPENDICES

Appendix A

Literature Review

Canola production has steadily expanded across Canada and is now the major oilseed crop grown, with 8,635,000 ha seeded in 2012 (Statistics Canada 2012). The main input cost for a canola crop is fertilizer; therefore, fertilizer use must be optimized for farmers to maximize returns. To improve profitability, beneficial management practices (BMP) that improve nutrient use efficiency are promoted by The Fertilizer Institute (2012), i.e. using the right source of fertilizer at the right rate at the right time in the right place. Due to the recent increase in yield potential of hybrid canola over conventional cultivars (Karamanos et al. 2005), the plant's nutrient requirements have increased. To achieve an average canola seed yield of 2520 kg ha^{-1}, the crop requires approximately 145-168 kg N ha^{-1}, 67-84 kg P_2O_5 ha^{-1}, 112-134 kg K_2O ha^{-1} and 30-31 kg S ha^{-1} (CFI 2001). Farmers need to adjust their fertilizer rates accordingly to achieve yield potential and maintain soil fertility. Although the response to P and S fertilizer in canola is well documented on the Canadian Prairies, tailoring BMPs for these nutrients using current farming practices requires further attention. The purpose of this chapter is to highlight the appropriate source, rate, timing and placement of P and S fertilizers for canola cropping systems on the Canadian Prairies.

A.1 Right Rate of Phosphorus and Sulphur for Canola

A.1.1 Sulphur Requirement for Canola

A.1.1.1 Sulphur Deficiency in Canola. Canola is particularly sensitive to S deficiency and requires more S compared to cereals because it has a higher protein content and proportion of S-containing amino acids (cysteine and methionine) and glucosinolates

(Grant and Bailey 1993). When the plant is S-deficient, the youngest parts of the plant are most affected because S is not mobile in the plant and cannot be translocated (Havlin et al. 2005). Canola plants suffering from S deficiency early in the growing season will exhibit stunted growth and purpling and cupping of the youngest leaves (Franzen and Grant 2008; Grant and Bailey 1993). Since S deficiency during any part of the growing season can reduce yield, a constant supply of S is required to optimize yields (Malhi and Gill 2007; Franzen and Grant 2008; Grant and Bailey 1993; Mahli et al. 2005). However, S demand is most crucial during flowering and seed-set, so early season S-deficient plants can recover if S is supplied at the rosette to bolting stage (Malhi and Gill 2002). In addition, canola seed quality, in particular oil concentration, can be improved with adequate S (Grant et al. 2003a).

A.1.1.2 Sulphur-Deficient Soil Management. Sulphur deficient soils are widespread across Canada and the area may be increasing due to decreased atmospheric deposition of S, and increased cropping intensity and removal by high yielding, high S demanding crops (Grant et al. 2012; Malhi et al. 2005). Sulphur deficiency is most common on Grey Luvisolic soils and the majority of the estimated 4 million ha of S-deficient soils on the Canadian Prairies are found on low organic matter, coarse textured soils with low rates of mineralization and high leaching potential (Doyle and Cowell 1993b). Sulphur is considered to be deficient for growing canola where there is less than 30-40 kg of sulphate (SO_4^{2-}) -S ha^{-1} in the top 0-60 cm of soil (Karamanos et al. 2007) or a water extractable N:S ratio less than 9 in the top 0-15 cm of soil (Bailey 1986).

Sulphur deficiency can also be exacerbated with increasing yield potential and rates of N fertilizer applied (Grant and Bailey 1993). Nitrogen and S requirements are linked because they are both required for protein and chlorophyll synthesis and therefore both influence biomass and seed yield (Grant et al. 2012). Malhi and Gill (2002) found that the rate of S fertilizer required to optimize canola seed yield and quality on S-deficient soils was proportional to the N supplied by the soil and fertilizer. However, on S-sufficient soils, Karamanos et al. (2007) found that seed yield increased with S application without balancing N and S fertilizer additions. Predicting an S response is difficult, using random composite soil sampling due to frequent spatially and temporally variable soil S (Grant et al. 2012); therefore, a moderate amount of S is usually recommended for canola to ensure that S deficiency does not occur.

A.1.1.3 Canola Sulphur Requirement. To reach full yield potential, canola above ground biomass should have an N:S ratio of 12 (Bailey 1986) and a concentration above 2.5 mg g^{-1} at the time of flowering (Grant et al. 2003b). The optimal soil N:S ratio is 5:1 to 8:1 (Grant et al. 2012) and in Canada, it is generally advised to apply N and S fertilizer in a 7:1 ratio (Canola Council of Canada 2011a). However, Karamanos et al. (2005, 2007) advised that N and S fertilizers do not need to be applied in a particular ratio once the crop has access to sufficient soil plus fertilizer N or S to avoid deficiency. Typically, recommended rates applied in canola are 15-30 kg S ha^{-1} (Grant et al. 2012; Malhi et al. 2005a), with 30 kg S ha^{-1} being enough to achieve maximum seed yield and S uptake on S-deficient soils (Malhi et al. 2007).

A.1.2 Phosphorus Requirement for Canola

A.1.2.1 Phosphorus Deficiency in Canola. As with S, canola requires more P than cereals (Grant and Bailey 1993). Phosphorus is an important constituent of both structural and energy transfer functions in the plant (Havlin et al. 2005). Grant et al. (2001) suggested that P-deficiency in the early parts of the growing season could lead to irreversible effects on crop growth and, therefore, P supply in the first 2-6 weeks is especially important for crop yield. Phosphorus is mobile within the plant and can be translocated to the youngest parts of the plant when the plant is P-deficient (Havlin et al. 2005). Deficiency symptoms will show up in the older leaves first and severely P-deficient plants may appear dark green/purple, are stunted in growth and later, the number of seeds per pod is reduced (Grant et al. 2001; Grant and Bailey 1993). Phosphorus has little effect on canola grain oil concentration but can increase protein content and adequate early season P nutrition can also lead to earlier maturity, which is important for grain yield and quality in short-season growing regions (Grant and Bailey 1993). Phosphorus, like S, is linked to protein synthesis and N and P concentration in the plant are correlated (Sheppard and Bates 1980). To obtain yield potential, P fertilizer does not have to be applied in proportion to N fertilizer (Sheppard and Bates 1980; Karamanos et al. 2005).

A.1.2.2 Phosphorus-Deficient Soil Management. Canola production is limited by P deficiency on most soils in Canada, according to the Canola Council of Canada (2011b). Because 90% of P taken up by the canola plant is removed with the grain (Doyle, 1993a) maintaining soil P fertility is a challenge. As rotations shorten and farmers grow canola more frequently, P-deficiency may increase if P additions do not equal P removal. For example, Malhi et al. (2011) found that soil extractable P in 0-15 cm soil was less in canola monocultures than four-year canola rotations including wheat and flax. Syers et al. (2008) advised that the critical P level could be maintained by balancing P removal with P additions; this strategy can improve economic return for farmers and decrease environmental risks. Therefore, it is important to apply an adequate amount of P to maintain soil fertility as well as reach yield potential.

A.1.2.3 Canola Phosphorus Requirement. The critical soil test P concentration, the point at which additional P does not increase crop yield (Syers et al. 2008), was suggested to be 10 mg kg^{-1} $NaHCO_3$ extractable P in top 0-15 cm soil for canola (Grant and Bailey 1993). More recently, Karamanos et al. (2002) confirmed this: at typical application rates of 20-40 kg P_2O_5 ha^{-1} hybrid canola frequently had a positive yield response on soils with less than 20 kg P ha^{-1} in the top 0-15 cm soil. At the time of flowering, optimal tissue concentration of P is between 0.25-0.5% (Grant and Bailey 1993); however, if tissue P is less than this critical value, it is often too late to recover from P deficiency at this point. Therefore, satisfying the nutrient requirement of P early in crop growth is important for attaining maximum crop yield (Grant et al. 2001) and a suitable amount of P should be applied at the time of seeding. This management practice is commonly referred to as "starter P". The right rate of fertilizer must be applied using an appropriate fertilizer source to adequately meet crop demand throughout the growing season.

A.2 Right Source of Phosphorus and Sulphur for Canadian Cropping Systems

A.2.1 Sulphur Sources

A.2.1.1 Plant Available Sulphur. On the Canadian Prairies, S forms most commonly used are sulphate (SO_4^{2-}, e.g., ammonium sulphate (AS)), thiosulphate ($S_2O_3^{2-}$, e.g. ammonium thiosulphate (ATS)) and elemental S (ES) (Grant et al. 2012). These three forms of fertilizers differ in their chemistry and availability for plants. Because plants take up S in the form of SO_4^{2-}-S, soil solution and adsorbed SO_4^{2-} represent the pool of plant available soil S (Havlin et al. 2005). Sulphate-S is mobile in the soil and soil reserves in the 30-60 cm depth can often supply S late in the growing season and reverse earlier S deficiency symptoms on soils with S-deficient surface layers (Bole and Pittman 1984). Soil organic matter mineralization can also supply a significant amount of SO_4^{2-} during the growing season (Kovar and Grant 2011). Many soils on the Canadian Prairies contain sub-surface reserves of calcium (Ca)- or magnesium (Mg)-SO_4^{2-} which can reduce the risk of S deficiency; however, the distribution of SO_4^{2-} and canola response to S fertilization is spatially variable (Franzen and Grant 2008). Soil SO_4^{2-}-S is also temporally variable due to seasonal fluctuation in plant uptake, S losses through leaching and S mineralization/immobilization which is influenced by soil organic matter, moisture, pH and temperature (Havlin et al. 2005). Because of the variable S content in soils across the landscape from year to year, farmers rely primarily on SO_4^{2-}-S fertilizers to supply immediately available S to their canola crop.

A.2.1.2 Sulphate and Thiosulphate. Studies conducted in western Canada have demonstrated that in the year of application AS is effective in increasing S tissue concentration at flowering (Grant et al. 2003b), oil concentration, S concentration in the seed (Grant et al. 2003a) and seed yield (Grant et al. 2004; Solberg et al. 2007). Although ATS must first be oxidized to form SO_4^{2-}-S, ATS and AS both release plant available SO_4^{2-}-S relatively quickly in soil (Janzen and Bettany 1986). Rate of oxidation of $S_2O_3^{2-}$ in the soil can be delayed with cold temperatures (< 5°C); at warmer temperatures (15-25°C) the oxidation rate would be quick enough to provide adequate amounts of SO_4^{2-} for seedlings (Goos and Johnson 2001a). Due to its rapid conversion to SO_4^{2-}-S, ATS is considered to be as effective at increasing seed yield and S uptake as AS for canola (Grant et al. 2012). Successive applications of AS also can build residual soil SO_4^{2-}-S (Malhi et al. 2009) to levels adequate for canola production.

A.2.1.3 Elemental Sulphur. Unlike AS and ATS, ES is completely reliant on microbial oxidation to be converted to plant available SO_4^{2-}-S (Malhi et al. 2005a). Since temperature, moisture, pH and soil OM affect microbial oxidation (Grant et al. 2012) the relatively cool and dry conditions in the Northern Great Plains are not reliably conducive for microbial oxidation of ES (Franzen and Grant 2008). Therefore, numerous studies have found that the rate of oxidation of ES fertilizers are often not rapid enough to provide sufficient SO_4^{2-}-S to achieve canola seed yield and/or quality potential in the year of application on S-deficient soils (Bole and Pittman 1984; Janzen and Bettany 1986; Grant et al. 2003a, 2003b; Malhi 2005; Malhi et al. 2005b). However, as particle size of ES decreases, the rate of oxidation and release of SO_4^{2-} can increase (Janzen and Bettany 1986; Malhi et al. 2005b). An ES product, Vitasul, is now formulated to disperse into small particles upon wetting in the soil, increasing the surface area for microbes to access it. With successive applications of ES, soil SO_4^{2-}-S concentrations may accumulate to sufficient levels for canola production (Solberg et al. 2007; Malhi et al. 2009).

A.2.1.4 Blended Products. To capitalize on the immediately available form of SO_4^{2-}-S from AS and slow-release characteristics of ES, fertilizer manufacturers have formulated blended products such as Mosaic's MicroEssentials S15 (MES15) which contains 50% sulphur in AS form and 50% in ES with the expectation that the product will provide a continuous supply of plant available SO_4^{2-}-S throughout the growing season. However, under field conditions, Grant et al. (2003b) found that a blend of AS and ES resulted in intermediate increases tissue S concentration and N:S ratio in at flowering, between AS and elemental S sources on S-responsive soils. Similarly, under both field and controlled environment conditions, Kroeker (2005) found that only the SO_4^{2-}-S from the MES15 appeared to be available to the crop in the year of application and the ES was not oxidized at a sufficient rate to be utilized by the crop in a significant amount.

A.2.2 Phosphorus Sources

A.2.2.1 Plant Available Phosphorus. Phosphorus in soil solution moves to the root primarily by diffusion, to a lesser extent by mass flow and a very small percentage by root interception (Kovar and Claassen 2005). Phosphorus must be in the soluble orthophosphate form, $H_2PO_4^-$ or HPO_4^{2-}, to be absorbed by plant roots and is taken up preferentially as $H_2PO_4^-$ (Kovar and Claassen 2005). Soil properties, such as pH, cation exchange capacity (CEC), buffering power, and Ca and Mg content, play important roles in regulating the amount and form of available P in soil, particularly in calcareous soils. Calcareous soils, which typically have a high CEC and a high Ca and Mg content, have a large capacity to retain P through adsorption to calcium carbonates and precipitation of P with Ca or Mg from adsorption sites or from the dissolved Ca from calcium carbonates (Akinremi and Cho 1991). The pH also affects the form of orthophosphate found in soil solution; the ratio of $H_2PO_4^-$ to HPO_4^{2-} decreases in alkaline soil (Kovar and Claassen 2005). Monohydrogen phosphate (HPO_4^{2-}) is also the orthophosphate specie that is most prone to precipitation with Ca, forming dicalcium phosphate dihydrate (DCPD) in alkaline soil (Akinremi and Cho 1991). However, in spite of these challenges for P availability, Bailey and Grant (1990) concluded that for canola production on the eastern Prairies, P uptake is not affected by calcium carbonate content.

Canola is relatively efficient at utilizing fertilizer P compared to wheat or flax because it has an exceptional capacity to proliferate its roots in the fertilizer reaction zone (Strong and Soper 1974). Canola can also increase P uptake by rhizosphere acidification.

Trolove et al. (2003) describes canola as a classic example of the alkaline uptake pattern: when excess cations are absorbed, H^+ is released to maintain electroneutrality in the root. Canola also releases organic acids to reduce the rhizosphere pH and solubilize P (Grant et. al, 2001). The lower pH caused an increase in the ratio of $H_2PO_4^-$ to HPO_4^{2-}, which decreased P and increased P absorption. Rhizosphere pH is further reduced if plants are fed NH_4^+-N. Miller et al. (1970) found that roots release H^+ when absorbing NH_4^+, effectively reducing the pH at the soil-root interface. Although canola is relatively efficient at utilizing fertilizer P, the fertilizer use efficiency for soluble P fertilizers seldom exceeds 20% in the year of application (Chien et al. 2011).

A.2.2.2 Monoammonium Phosphate. Monoammonium phosphate (MAP) is the most popular source of P fertilizer used by Canadian farmers. Dicalcium phosphate dihydrate is the first reaction product of MAP and other soluble P fertilizers in soils with a pH between 6 and 8.5 (Doyle and Cowell 1993) and in calcareous soils (McLaughlin et al. 2011). Although it is sparingly soluble, plants can absorb only soluble orthophosphate anions, so DCPD must be dissolved before plants can utilize it. Ammonium ions have been found to improve solubility and uptake of fertilizer P due to the phenomenon called the "ammonium ion effect" (Flaten 1989). A combination of NH_4^+ -stimulated plant-induced changes to the rhizosphere and root morphology and physiology likely increases the uptake of P in the fertilizer band. As previously discussed, rhizosphere acidification can increase P availability because the pH is reduced in the surrounding soil when H^+ are released with NH_4^+ uptake. Soil exploitation can increase P uptake by increasing the soil-root contact and can be achieved by stimulating root and root hair growth as well as decreasing the diameter of the roots (Kovar and Claassen 2005). It has been proposed that NH_4^+ stimulates root growth by decreasing root redox potentials, loosening the cell wall matrix, accelerating cell division and requires less energy for assimilation than the other plant available N source, NO_3^- (Jing et al. 2010). Ammonium is also the preferred source of N over NO_3^- at early growth stages (Rennie and Soper 1958), which could promote early season biomass production. Another way NH_4^+ may improve root P absorption is by coupling the absorption of NH_4^+ with $H_2PO_4^-$. Ammonium absorption encourages $H_2PO_4^-$ absorption (Flaten 1989) because the opposite charges allow the root to maintain electroneutrality.

Because of these "ammonium ion effects", most phosphorus fertilizers used in Canada are ammoniated phosphates, with MAP being the most popular. The use of diammonium phosphate (DAP) is not appropriate for most Canadian crops and soils because of the risk of seed-row N toxicity from this product. In addition, DAP results in an increase in the soil solution pH and consequently an increase in calcium-phosphate precipitates compared to MAP (Moody et al. 1995).

Researchers from Australia have found improved P use efficiency from liquid formulations of MAP compared to granular MAP. Holloway et al. (2001) found under dry field conditions of southeastern Australia, fluid MAP increased P uptake and grain yield. However, the results were highly dependent on soil type; fluid P fertilizer was particularly effective on highly calcareous soils. Lab experiments conducted by Lombi et al. (2004) led to the hypothesis that the difference between the fluid and granular formulations was due to the greater rate of P diffusion into the soil from fluid P, effectively increasing the amount of P in the fertilizer reaction zone. Their explanation for this phenomenon was that the fertilizer granule is highly hygroscopic causing capillary flow of water to flow in the opposite direction of P diffusion. The liquid formulation decreases the flow of water to the droplet, allowing more P to diffuse directly away from the site of application.

A.2.2.3 Ammonium Polyphosphate. Liquid ammonium polyphosphate (APP) is also used in Canadian canola cropping systems. Typical formulations contain <50% orthophosphates and >50% in the pyro- and tri-polyphosphate form (Hedley and McLaughlin 2005). Polyphosphates are quickly hydrolyzed to orthophosphates in soil and the rate of hydrolysis increases with increasing coarse soil texture, OM, pH, temperature and moisture (Hedley and McLaughlin, 2005). Polyphosphates, however, can form chelates with Ca, Mg, Fe and Al and therefore have greater mobility than orthophosphates in soil, particularity in alkaline and/or calcareous soil where hydrolysis is reduced (Hedley and McLaughlin, 2005). Under controlled environment conditions, Leytem and Westermann (2005) found that liquid APP increased bicarbonate extractable soil P at 4 weeks after seeding and shoot P accumulation of barley compared to MAP on low and high P soils. Although there is compelling evidence to believe liquid APP may be a more efficient P source than granular MAP, most research in North America has found that the two sources are equal in P availability for most crops, on most soils (Chien et al. 2011).

A.3 Right Placement and Timing of Phosphorus and Sulphur for Canola

A.3.1 Placement and Timing for Sulphur

Placement and timing have a significant influence on the availability of different sources of S fertilizers. Environmental factors, such as microbial populations, soil texture and soil moisture will influence the right placement and timing of application of SO_4^{2-}/S_2O_3

and ES fertilizers. In addition, managing S in the year of application versus long-term S fertility will also influence the management decisions.

A.3.1.1 Placement and Timing for Sulphate and Thiosulphate. Application of SO_4^{2-}-S at seeding is generally regarded to be the most efficient and effective timing for improved S uptake and seed yield and quality on S-deficient soils (Malhi and Gill 2002). As for placement, under controlled environment conditions S uptake increased with an increasing proportion of the root zone fertilized with sulphates and banding sulphate fertilizer within 36 cm of the surface produced the greatest canola yields (Bole and Pittman 1984). However, under field conditions, efficient placement of SO_4^{2-}-S sources is largely dependent on rainfall. Because SO_4^{2-} is mobile in the soil, broadcast applications will allow SO_4^{2-} to leach into the root zone with adequate rainfall; however, under dry conditions, broadcast SO_4^{2-} can be stranded on the surface and thus pre-plant banding, side- or seed-row banding is the most reliable method for placing SO_4^{2-} in a favourable position for plant uptake (Grant and Bailey 1993; Malhi et al. 2005a). Under eastern Prairie field conditions, seed-placed, pre-plant banded or spring broadcast AS produced similar effects on tissue S concentration, tissue N:S ratio (Grant et al. 2003b) and yield (Grant et al. 2004) under conventional and reduced tillage systems. Ammonium sulphate was sometimes less effective in increasing tissue S concentration when broadcast in the fall compared to spring (Grant et al. 2003b), perhaps due to losses from leaching. Seed-placed AS was found to decrease oil concentration of the seed when seed-row toxicity occurred, reducing plant stand and delaying maturity, compared to broadcast and pre-plant banding (Grant et al. 2003a). With seed-placed AS, seed-row toxicity can be a concern and rates should be adjusted accordingly under different moisture and seed-bed utilization conditions (Grant et al. 2012). As previously mentioned, $S_2O_3^{2-}$ rapidly converts to SO_4^{2-} in the soil, and therefore, optimal placement and timing options for ATS are the same as for AS (MAFRI 2007).

A.3.1.2 Placement and Timing for Elemental Sulphur. As previously discussed, ES is completely reliant on microbial oxidation to release plant available SO_4^{2-}-S. Thus maximizing time and surface area exposed to microbes will increase oxidation. Sulphate-sulphur release rates generally increase with increasing particle distribution and decreasing particle size (Janzen and Bettany 1986); therefore, it is recommended that ES be broadcast and/or incorporated as far in advance of the target crop as possible (Grant and Bailey 1993). Banding and seed-placement is not recommended for ES in the year of planting the target crop (Grant et al. 2012) because ES forms a hydrophobic band restricting microbial oxidation (Janzen and Bettany 1986). Under field conditions, broadcast or incorporation of ES resulted in greater canola yields than banding ES, but results were not equal to SO_4^{2-}-S sources (Solberg et al. 2007). Broadcasting in fall also increased oxidation of ES compared to spring broadcasting, but again, response was not equal to SO_4^{2-}-S sources (Malhi et al. 2009).

A.3.2 Placement and Timing for Phosphorus

Because P is relatively immobile in the soil and early season crop requirements for P are large, Grant et al. (2001) reported that placing fertilizer P in a band near or with the seed is an efficient P management strategy. Banding fertilizer P reduces soil-fertilizer contact and places fertilizer in a favourable position for roots to encounter the nutrient rich patch. This effectively increases fertilizer use efficiency, especially in low-P soils (Havlin et al. 2005) and in the year of application (Syers et al. 2008) compared to broadcast applications. Since the amount of P absorbed by the plant is a function of root-soil contact, P deficient plants can increase their root surface area to access more P (Kovar and Claassen 2005). Roots can respond to localized P supply by increasing lateral roots and root hairs and can maintain biomass production and P content by improving P uptake in the localized region (Drew and Saker 1978). Canola has an exceptionally large capacity to proliferate in a band of fertilizer P (Strong and Soper 1974). Even when soil P levels are high, applying a small amount of P near or with the seed, "starter P", often results in a P response early in the growing season. The placement of starter P near the seed is important for crops grown in areas with short growing seasons, cooler temperatures or wet soil (Havlin et al. 2005). These crops may have limited root development (Havlin et al. 2005) and soil P diffusion (Kovar and Claassen 2005) and desorption rates are slower in cooler soils (Sheppard and Racz 1984). In Canadian Prairie field studies, seed-placed MAP consistently increased canola grain yield (Bailey and Grant 1990; Karamanos et al. 2002; Lemke et al. 2009; Grant et al. 2009). However, seed-placed P reduced plant stand compared to side-band placement (Bailey and Grant 1999; Lemke et al. 2009).

A.3.3 Canola Plant Stand and Seed Yield

Farmers on the Canadian Prairies are advised to seed canola at a rate of 5.6-9 kg ha^{-1} (Canola Council of Canada 2011a). However, because seed size differs by seed lot and cultivar, seeding by rate of seeds is recommended over seeding by weight to achieve a satisfactory plant stand (Hanson et al. 2008). Due to physical and biological environmental constraints, 60-80% of seeds will emerge under the best conditions and only 40-60% will emerge under normal conditions; therefore, it is recommended to target a plant stand between 40-200 plants m^{-2} (Canola Council of Canada 2011). McGregor

(1987) found that reducing the plant stand from more than 100 plants m^{-2} to less than 40 plants m^{-2} reduced seed yield by 20%. Increasing seeding rate may increase yield; however, percent emergence will decrease with increasing seeding rates due to self-thinning (Hanson et al. 2008). Although seed-placed fertilizer can decrease plant stand, Grant et al. (2010) and Johnston et al. (2001, 2002) found that lower plant stands did not consistently reduce seed yield. Canola has an exceptional capacity to maintain high yields across a wide range of plant densities; yield compensation at lower plant densities comes from increasing number of pods per plant, seeds per pod and seed weight (Krogman and Hobbs 1975). However, as fertilizer inputs increase, higher plant stands are required to take advantage of the high nutrient levels and maximize yields (Brandt et al. 2007). Also, although comparable yields can be achieved over a range of plant densities, lower densities can delay maturity (McGregor 1987; Grant et al. 2010; Johnston et al. 2002).

A.3.4 Toxicity of Seed-Placed Fertilizers to Canola

Canola is known to be more sensitive to seed-placed fertilizers than cereal crops (Nyborg 1961). Seed-placed AS applied at a recommended rate of 20 kg S ha^{-1} can cause enough toxicity to reduce plant stands, which can subsequently reduce yield potential (Grant et al. 2004). Safe-rates of seed-placed P are generally restricted to 22 kg or less P_2O_5 ha^{-1} as MAP (MAFRI 2007), although farmers would like to apply more P to satisfy crop requirements and maintain yield potential. Nyborg and Hennig (1969) reported that under field conditions, 23 kg P_2O_5 ha^{-1} of seed-placed ammonium phosphate reduced plant stand by a third but still allowed the crop to reach yield potential; however, large rates (45-89 kg P_2O_5 ha^{-1}) reduced the capacity of the crop to reach yield potential due to a severe reduction in plant stand.

Canola is especially sensitive to compound fertilizers or fertilizer blends that contain nitrogen (N), where, in addition to the osmotic potential of a fertilizer, ammonia toxicity can also decrease seedling emergence and increase time to emergence, leaving seedlings vulnerable to insects and diseases (Dowling 1996). Farmers are also moving towards one-pass low disturbance low seed-bed utilization seeding systems where blended seed-placed P and S fertilizers are very concentrated near the seed, increasing potential seedling damage from salts and/or NH_3.

A.3.4.1 Salt Toxicity. Osmotic stress decreases root growth in fertilizer bands (Moody et al. 1995b); therefore, placing fertilizers in the seed-row could inhibit growth of seedlings. Canola seedling emergence was significantly more sensitive than chickpeas and wheat to increasing osmotic pressure (Dowling 1996). The relative salt index of P fertilizers is generally less than for S fertilizers. For example, the salt indexes for MAP and APP are 26.7 and 20.0, respectively, while the salt indexes for AS and ATS are 88.3 and 90.4, respectively (Havlin et al. 2005). Increasing seedbed utilization (SBU) and soil moisture at the time of seeding will dilute fertilizer salts and decrease osmotic stress on seedlings (Nyborg and Hennig 1959). Post-plant rainfall also plays a role; Dowling (1998) found that adding water to the seed-row at the time of seeding increased seedling emergence when rates of fertilizer higher than recommended were applied.

A.3.4.2 Ammonia Toxicity. Selecting the source and rate for seed-placed fertilizers should be based on NH_3 toxicity risk in addition to potential salt stress. Canola was found to be less tolerant of seed-row NH_3 compared to barley, wheat, chickpeas and canaryseed (Dowling 1996). Conventional sources of fertilizer P and S used in canola production are formulated with N; therefore, there is some risk of NH_3 toxicity with these P and S fertilizers. Monoammonium phosphate is considered to have relatively low NH_3 toxicity because the saturated solution of MAP has a pH of 3.5 (Hedley and McLaughlin 2005) and nitrification of NH_4^+ lowers the pH of the fertilizer band (Doyle and Cowell 1993) both of which favour NH_4^+ over NH_3. Because there is a higher N concentration in AS compared to MAP, the NH_3 toxicity risk for AS is considered greater. Therefore, AS is considered to be as toxic as urea-ammonium-nitrate and urea (MAFRI 2007).

In addition to fertilizer source, soil properties such as soil pH, CEC, texture, temperature and water content will also affect rate and amount of ammonia formation (Fenn and Kissel 1973). Calcareous soils in particular increase the risk of NH_3 toxicity of AS. Ammonium sulphate reacts with the $CaCO_3$ in the soil, forming ammonium carbonate ($(NH_4)_2CO_3$) and calcium sulphate ($CaSO_4$) (Eq. 1). The $CaSO_4$ precipitates, which drives the reaction to the right. The $(NH_4)_2CO_3$ spontaneously decomposes, releasing ammonia and carbon dioxide (Eq. 2), decreasing the pH of the surrounding soil (Eq. 3) (Fenn and Kissel 1973).

$$(NH_4)_2SO_4 + CaCO_3 \leftrightarrow (NH_4)_2CO_3 + CaSO_4 \quad (1)$$

$$(NH_4)_2CO_3 + H_2O \leftrightarrow 2NH_3\uparrow + H_2O + CO_2\uparrow \leftrightarrow 2NH_4OH \quad (2)$$

$$NH_4^+ + OH^- \leftrightarrow NH_4OH \leftrightarrow NH_3\uparrow + H_2O \quad (3)$$

A.4 Novel Fertilizers and Fertilizer Blends

A.4.1 Reduced Seedling Toxicity

A.4.1.1 Coated MAP. Polymer coated MAP (cMAP) was designed to increase fertilizer use efficiency by minimizing the fertilizer-soil contact, thus reducing P precipitation and releasing soluble P to match crop requirement throughout the growing season. Because the coating reduces the dissolution and diffusion of fertilizer salts, especially early in the growing season, it could also reduce seedling toxicity. Qian et al. (2010) found that although uncoated MAP caused seedling damage at 30-40 kg P_2O_5 ha^{-1} in canola, cMAP could be applied at rates of up to 80-100 kg P_2O_5 ha^{-1} without a significant reduction in plant stand. They suggested that cMAP could ideally be used as an alternative for MAP if there was concern with sensitive crops, high application rates, dry soils or low disturbance, low SBU seeding systems.

A.4.1.2 Elemental Sulphur Formulations. Elemental sulphur fertilizers are less toxic than SO_4^{2-}/$S_2O_3^{2-}$ fertilizers because unlike AS or ATS, ES does not contain N, so there is no risk of ammonia toxicity; in addition, ES contains no soluble salts and oxidizes slowly in soil and therefore has a much lower salt index than SO_4^{2-} (Grant et al. 2004). Novel products such as Vitasul, which is 100% ES and MES15, which is 50% S_o and 50% AS, could be less toxic than conventional SO_4^{2-} sources and therefore improve seedling emergence of sensitive crops such as canola.

A.4.1.3 Safening effect of MAP on AS. Applying P fertilizers can decrease the pH of the soil, reduce NH_3 formation and volatilization from urea (Akhtar and Naeem 2012), and improve seedling emergence (Fan and Mackenzie, 1995). Unlike the soil reaction zone for urea, the reaction zone for AS is normally acidic; however, in calcareous soil the reaction between AS and $CaCO_3$ increases the pH of the soil surrounding the fertilizer. Fenn (1975) found that substituting just 30% of AS with MAP decreased the formation of

NH_4CO_3 (Eq. 1) which subsequently reduced ammonia formation compared to that for AS applied alone.

A.4.2 Improved P uptake

As previously discussed, soluble P fertilizers such as MAP and APP are converted to DCPD in alkaline soils. Ammoniated ortho- and polyphosphates are efficient fertilizer sources because ammonium can increase P uptake and availability through plant-induced changes to the rhizosphere pH and root morphology and physiology. Blending P with S has also shown to be effective in increasing P uptake and availability by decreasing soil pH, reducing Ca-P precipitation and increasing P fertilizer reaction zones. Consequently, soluble P fertilizers formulated with ES and ammoniated SO_4^{2-} are now available (McLaughlin et al. 2011). Polymer coated MAP is also another formulation that decreases P precipitation and can increase P uptake.

A.4.2.1 Dual Banded Phosphorus and Sulphur. As early as 1958, Rennie and Soper observed an increase in P uptake in barley with dual banded AS and MAP (Rennie and Soper 1958). Ammonium sulphate improves P solubility by decreasing the pH of the fertilizer reaction zone when AS is oxidized, therefore, increasing the solubility of DCPD (Kumaragamage 1991) and increasing the $H_2PO_4^-$: HPO_4^{2-} ratio (Olatuyi et al. 2009b).

In addition to solubilising DCPD, SO_4^{2-} also helps to maintain the orthophosphate in a soluble form and reduce the precipitation of P with Ca. Moody et al. (1995a) found that the Ca concentration in solution was lower closer to the fertilizer band with AS than that of the bulk soil and attributed this to Ca-SO_4^{2-} precipitation. Kumaragamage et al. (2004) explained that P solubility and diffusion was increased by AS because the dissolved sulphate anion competes with phosphate anions for precipitation reactions with calcium, which decreased the concentration of soluble calcium available to react with P. Another possible mechanism of reduced Ca concentration in the fertilizer band and hence Ca-P precipitation is the proposed theory of "snowploughing". This occurs when NH_4^+ displaces Ca from adsorption sites and pushes these cations "ahead" away from the fertilizer reaction zone (Beever 1987). Flaten (1989) found that the highest concentrations of water extractable Ca was at the 5-6 cm distance from the application site with either NH_4^+ or K^+ added to MAP. Sulphate ions paired with cations such as NH_4^+ move ahead of the soluble P precipitating with any soluble Ca, reducing the amount of Ca in solution and preventing Ca from diffusing toward the fertilizer reaction zone (Olatuyi 2009b). The salts in contact with the Ca-P fertilizer influences the Ca-P precipitates that remain as Ca-P compounds near the granule, the amount and distance of P movement into the surrounding soil and the solubility of the reaction products but are also largely dependent on the soil properties (Bouldin and Sample 1985).

Adding non-phosphatic SO_4^{2-} salts to phosphate fertilizers has also been found to improve the movement and transport of phosphate in soil (Kumaragamage et al. 2004; Miller and Vij 1962). Larger fertilizer reaction zones should increase root absorption of P (Havlin 2005) by allowing the roots to intercept the patch of P-rich soil more easily and also enhance root proliferation in that zone (Beever 1987). In model wax columns, Olatuyi et al. (2009a, 2009b) found that P diffused 6 mm from the application zone with AS and MAP compared to 4.2 mm for MAP alone. However, in soil studies the results are inconsistent and the variability in the movement and effectiveness of SO_4^{2-} in soil can be attributed to soil type (Moody et al. 1995a).

Recently, field studies have also shown that AS, ATS and ES can also improve the early season P uptake of wheat fertilized with APP (Goos and Johnson 2001b). Both

ATS and ES fertilizers also acidify the soil when microbial oxidation releases H^+ when $S_2O_3^{2-}$ or ES is converted to SO_4^{2-} (Havlin et al. 2005). By banding ATS with MAP, Morden et al. (1986) observed a decrease in pH in the fertilizer reaction zone as $S_2O_3^{2-}$ was oxidized and subsequent increase in P uptake for barley. However, Kroeker et al. (2005) found no increase in P uptake or dry matter accumulation in wheat or canola with a homogenous fertilizer granule containing MAP, AS and elemental S or when AS or ES was added to MAP over the MAP alone treatment under field conditions.

A.4.2.2 Coated MAP. Polymer coatings on MAP were designed to minimize the fertilizer-soil contact, thus increasing fertilizer use efficiency by reducing P precipitation and releasing soluble P to match crop requirement throughout the growing season. Unlike polymer coated N, water content of the soil does not play an important role in regulating the amount of P released. Since P moves by diffusion, soil temperature and coating thickness are more important in regulating available P movement from the granule (Zhang et al. 2000). Pauly et al. (2002) found that in early growth stages, P uptake and dry matter yield was lower with cMAP than MAP; however, the opposite was true in later growth stages, indicating that P release of cMAP matched plant requirements more effectively than MAP. Similarly, Leytem and Westermann (2005) found that although uncoated MAP produced significantly more bicarbonate extractable P in both low and high P soils than cMAP, cMAP produced a greater shoot P accumulation than MAP in high P soils. However, for canola and wheat, Qian et al. (2010) measured very little difference in P uptake and dry matter yield between seed-placed cMAP and MAP at early growth stages. This was attributed to the seedling damage that occurred with higher rates of seed-placed MAP and the potential adsorption and precipitation of the small amount of P that had been released from cMAP. Available P from cMAP may also be insignificant on low P or high CEC soils where it is quickly adsorbed (Leytem and Westermann 2005).

A.5 Conclusion

Canola requires relatively large amounts of P and S to optimize yield potential. Since farmers generally place their P and S fertilizer with the seed for convenience and nutrient efficiency, rates of P and S are restricted to reduce seedling damage. There are no guidelines regarding the maximum safe rate of blended P and S placed in the seed-row. In addition, fertilizer toxicity can vary by source and soil properties. Soil pH, CEC, $CaCO_3$ content, moisture content could increase the risk of NH_3 toxicity of AS in particular. Novel fertilizers could be more seed safe than conventional fertilizers, and therefore could increase the rates that could be safely applied with the seed. The current recommended safe rates for seed-placed P and S are lower than the crop requirement, and therefore could limit yield potential.

Although seed-placed fertilizer can reduce plant stands, lower plant densities do not always result in lower seed yields because canola can compensate by increasing vegetative growth. Sources and rates of seed-placed fertilizer therefore must be applied to maximize plant available nutrients while maintaining adequate plant stand.

Appendix B

Plant Stand Means of Canola at Two Weeks after Emergence in Field Study (Chapter 2)

Table B.1a Plant stand (plants m^{-2}) mean of canola two weeks after emergence by treatment at the Brandon and Carman, MB sites

	Brandon			Carman		
Treatment	2010	2011	2012	2010	2011	2012
Control	61	46	99^{abc}	58	103^{a}	70
Low AS	50	56	69^{defgh}	73	83^{bc}	60
Low ATS	59	56	70^{defgh}	61	-	72
High AS	51	53	82^{bcde}	62	74^{c}	73
High ATS	49	33	53^{gh}	68	-	65
Low MAP	73	62	82^{bcde}	59	76^{bc}	76
Low APP	49	48	73^{cdefg}	61	-	72
Low cMAP	65	58	94^{abcd}	53	100^{a}	85
Low MES15	76	50	79^{bcdefg}	54	92^{ab}	81
Low MAP/low AS	38	46	74^{cdefg}	49	78^{bc}	60
Low cMAP/low AS	67	56	119^{a}	53	79^{bc}	53
Low APP/low ATS	54	43	56^{efgh}	61	-	56
Low MAP/high AS	62	48	54^{fgh}	50	51^{de}	65
Low cMAP/highAS	59	69	84^{bcd}	42	74^{c}	63
Low APP/high ATS	56	44	56^{efgh}	67	-	67
High MAP	59	43	81^{bcdef}	43	67^{cd}	63
High APP	52	43	73^{cdefg}	53	-	59
High cMAP	74	51	92^{abcd}	56	93^{ab}	68
High MAP/low AS	52	46	76^{bcdefg}	38	66^{cd}	62
High cMAP/low AS	64	49	103^{ab}	41	73^{c}	62
High APP/low ATS	52	32	74^{cdefg}	69	-	71
High MES15	53	36	98^{abc}	60	68^{c}	69
High MAP/high AS	46	49	78^{bcdefg}	33	45^{e}	64
High cMAP/high AS	61	51	78^{bcdefg}	53	73^{c}	64
High APP/high ATS	43	46	43^{h}	55	-	61
High MAP/high Vitasul	75	59	86^{bcd}	53	80^{bc}	64
Mean	58	49	78	55	76	66
C.V.	40.3	33.5	31.1	63.1	24.2	24.3
df	25	25	25	25	17	25
F-value	1.25	1.13	3.11	2.46	6.42	0.83
$P > F$	NS	NS	<.0001	NS	<.0001	NS

[a-h] Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

Table B.1b Plant stand (plants m^{-2}) mean of canola two weeks after emergence by treatment at the Kelburn, MB and Normandin, QE sites

	Kelburn		Normandin		
Treatment	2011	2012	2010	2011	2012
Control	89^{abcdef}	99	117^{ab}	84^{abcd}	68^{a}
Low AS	85^{bcdef}	88	113^{bcd}	81^{bcde}	52^{abcde}
Low ATS	103^{ab}	90	-	-	-
High AS	74^{def}	91	88^{fgh}	79^{bcde}	68^{a}
High ATS	105^{a}	74	-	-	-
Low MAP	87^{abcdef}	89	109^{bcde}	84^{abcd}	46^{bcde}
Low APP	94^{abcde}	95	-	-	-
Low cMAP	79^{cdef}	141	132^{a}	95^{ab}	63^{abc}
Low MES15	78^{cdef}	92	104^{bcdef}	69^{cdefg}	39^{de}
Low MAP/low AS	74^{ef}	110	96^{defg}	76^{cdef}	59^{abcd}
Low cMAP/low AS	95^{abc}	83	120^{ab}	79^{bcde}	59^{abcd}
Low APP/low ATS	94^{abcd}	90	-	-	-
Low MAP/high AS	78^{cdef}	69	83^{gh}	55^{g}	44^{cde}
Low cMAP/highAS	73^{f}	72	94^{efg}	64^{efg}	58^{abcd}
Low APP/high ATS	87^{abcdef}	73	-	-	-
High MAP	83^{cdef}	93	91^{fgh}	66^{efg}	50^{abcde}
High APP	75^{cdef}	83	-	-	-
High cMAP	74^{def}	81	115^{abc}	102^{a}	66^{ab}
High MAP/low AS	80^{cdef}	95	83^{gh}	66^{defg}	36^{e}
High cMAP/low AS	69^{f}	62	118^{ab}	86^{abc}	63^{abc}
High APP/low ATS	75^{cdef}	83	-	-	-
High MES15	86^{abcdef}	72	104^{bcdef}	71^{cdefg}	43^{cde}
High MAP/high AS	81^{cdef}	66	76^{h}	53^{g}	41^{de}
High cMAP/high AS	74^{def}	81	92^{efgh}	64^{efg}	47^{bcde}
High APP/high ATS	79^{cdef}	88	-	-	-
High MAP/high Vitasul	85^{abcdef}	72	99^{cdefg}	60^{fg}	49^{abcde}
Mean	83	86	102	74	53
C.V.	18.7	31.2	18.4	23.5	30.6
df	25	25	17	17	17
F-value	1.69	1.63	5.91	4.25	1.99
$P > F$	.0471	NS	<.0001	<.0001	.0284

$^{a-h}$ Means followed by the same letter grouping are not significantly different $P < 0.05$; NS indicates that the treatment effect was not significant at $P < 0.05$

Appendix C

Regression Analysis to Determine Relationship between Plant Stand and Seed Yield of Canola (Chapter 2)

Table C. 1 Regression equations for influence of plant stand on seed yield at each site year

Site	Year	*F*-value	*P* > *F*	Regression Equation	R^2 value
Brandon	2010	0.4500	0.5109	y = 1753.1 + 5.4624x	0.0182
	2012	2.0200	0.1681	y = 908.0 + 5.5209x	0.0776
Carman	2010	3.2000	0.0864	y = 1858.0 + 2.5893x	0.1176
	2011	0.0300	0.8579	y = 1448.4 + 1.9655x	0.0021
	2012	1.0600	0.3141	y = 1494.6 + 3.6040x	0.0422
Kelburn	2011	0.0800	0.7828	y = 1868.8 - 1.2786x	0.0032
	2012	0.0600	0.8066	y = 1555.1 + 1.0049x	0.0025
Lethbridge	2010	12.6200	0.0016	y = 281.1 + 11.8032x	0.3447
	2011	2.2800	0.1440	y = 220.6 + 38.8818x	0.0868
	2012	0.0600	0.8083	y = 1781.8 -1.3254x	0.0025
Normandin	2010	6.1100	0.0250	y = 3964.1 - 5.2877x	0.2765
	2011	5.6900	0.0298	y = 4650.5 - 13.4539x	0.2623
	2012	5.4400	0.0330	y = 5115.2 - 12.7997x	0.2538
Thunder Bay	2010	1.4800	0.2412	y = 1599.4 + 17.4138x	0.0847
	2011	4.9500	0.0408	y = 4445.6 - 13.6917x	0.2363
	2012	4.3300	0.0539	y = 4097.8 - 13.2918x	0.2129

Appendix D

Analysis of Variance and Mean Separation of Treatments in the Growth Chamber Study (Chapter 3)

Table D.1 Main effects means of landscape position, MAP rate, AS rate and days after emergence on plant stand (plants m^{-2}) on soil from the Minnedosa and Nesbitt, MB sites

		Site	
Main effect	Level	Minnedosa	Nesbitt
Landscape Position	Depression	190^{a}	169^{a}
	Hilltop	170^{b}	118^{b}
MAP rate	0	194^{a}	163^{a}
	Low	187^{a}	165^{a}
	High	159^{b}	103^{b}
AS rate	0	186^{a}	174^{a}
	Low	181^{ab}	143^{b}
	High	173^{b}	114^{c}
Days after emergence	0	-	96^{h}
	2	156^{d}	118^{g}
	4	171^{c}	130^{f}
	6	177^{b}	136^{e}
	8	181^{a}	142^{d}
	10	182^{a}	147^{c}
	12	183^{a}	151^{b}
	14	184^{a}	154^{a}
	16	184^{a}	156^{a}
	18	184^{a}	156^{a}
	20	184^{a}	156^{a}
	22	184^{a}	155^{ab}
	24	184^{ab}	153^{abc}
	26	184^{ab}	152^{abc}
	28	183^{ab}	153^{abc}

$^{a-h}$ Mean followed by same letter grouping for each main effect at each site are not significantly different $P < 0.05$

Table D.2 Interacting effect of AS rate and landscape position on plant stand (plants m^{-2}) of canola on soil from the Minnedosa, MB site

	Landscape position	
AS rate	Depression	Hilltop
0	188^{a}	184^{ab}
Low	196^{a}	166^{bc}
High	187^{a}	160^{c}

$^{a\text{-}c}$ Means followed by the same letter grouping are not significantly different $P < 0.05$

Table D.3 Interacting effect of MAP rate and days after emergence on plant stand (plants m^{-2}) of canola on soil from the Minnedosa, MB site

Days after emergence	MAP rate		
	0	Low	High
2	173^a	170^a	126^b
4	187^a	184^a	141^b
6	191^a	188^a	152^b
8	195^a	189^a	159^b
10	196^a	189^a	161^b
12	196^a	189^a	164^b
14	197^a	189^a	165^b
16	197^a	189^a	165^b
18	197^a	191^a	165^b
20	198^a	190^a	165^b
22	196^a	190^a	166^b
24	197^a	188^a	166^b
26	197^a	189^a	165^b
28	196^a	189^a	166^b

$^{a\text{-}b}$ Means within the same row followed by the same letter grouping are not significantly different $P < 0.05$

Table D.4a Interacting effect of landscape position, MAP rate, AS rate and days after emergence on canola plant stand (plants m^{-2}) on soil from the Nesbitt, MB site at 0-12 days after emergence

			Days after emergence						
Landscape position	AS rate	MAP rate	0	2	4	6	8	10	12
Depression	0	0	191^{a}	194^{a}	199^{a}	207^{a}	207^{a}	202^{a}	207^{a}
Depression	Low	0	170^{ab}	183^{ab}	186^{ab}	191^{ab}	191^{abc}	194^{ab}	191^{ab}
Depression	High	0	116^{abcdef}	140^{abcd}	156^{abc}	170^{abc}	178^{abcd}	183^{abc}	188^{ab}
Depression	0	Low	170^{ab}	183^{ab}	188^{ab}	188^{ab}	194^{abc}	194^{ab}	194^{ab}
Depression	Low	Low	137^{abcd}	170^{abc}	178^{ab}	180^{ab}	180^{abcd}	180^{abc}	183^{abc}
Depression	High	Low	118^{abcde}	167^{abc}	167^{abc}	170^{abc}	172^{abcd}	175^{abc}	172^{abc}
Depression	0	High	105^{abcdef}	145^{abcd}	159^{abc}	159^{abc}	164^{abcd}	167^{abcd}	172^{abc}
Depression	Low	High	54^{cdef}	81^{bcde}	100^{bcdef}	121^{bcd}	129^{cde}	140^{abcd}	143^{bcd}
Depression	High	High	65^{bcdef}	91^{abcde}	126^{abcd}	129^{abcd}	132^{bcde}	135^{bcd}	137^{bcde}
Hilltop	0	0	180^{a}	194^{a}	196^{a}	199^{ab}	202^{ab}	202^{a}	207^{a}
Hilltop	Low	0	57^{cdef}	86^{bcde}	121^{abcde}	135^{abcd}	148^{abcde}	159^{abcd}	161^{abcd}
Hilltop	High	0	16^{ef}	30^{e}	32^{ef}	32^{e}	40^{g}	48^{fg}	54^{fg}
Hilltop	0	Low	140^{abc}	167^{abc}	188^{ab}	191^{ab}	196^{abc}	194^{ab}	199^{ab}
Hilltop	Low	Low	105^{abcdef}	143^{abcd}	140^{abcd}	145^{abcd}	151^{abcde}	153^{abcd}	156^{abcd}
Hilltop	High	Low	46^{cdef}	73^{cde}	86^{cdef}	94^{cde}	113^{def}	118^{cde}	124^{cde}
Hilltop	0	High	30^{def}	48^{de}	65^{def}	75^{de}	86^{efg}	105^{def}	105^{def}
Hilltop	Low	High	19^{ef}	22^{e}	32^{ef}	38^{e}	48^{fg}	65^{efg}	75^{efg}
Hilltop	High	High	8^{f}	13^{e}	16^{f}	16^{e}	24^{g}	35^{g}	40^{g}

$^{a\text{-}g}$ Means within the same column followed by the same letter grouping are not significantly different $P < 0.05$

Table D.4b Interacting effect of landscape position, MAP rate, AS rate and days after emergence on canola plant stand (plants m^2) on soil from the Nesbitt, MB site at 14-28 days after emergence

			Days after emergence							
Landscape position	AS rate	MAP rate	14	16	18	20	22	24	26	28
Depression	0	0	207^{a}	207^{a}	207^{a}	207^{a}	207^{a}	205^{a}	202^{a}	207^{a}
Depression	Low	0	194^{ab}	194^{ab}	194^{a}	194^{ab}	194^{ab}	191^{ab}	191^{abc}	191^{ab}
Depression	High	0	186^{abc}	188^{ab}	188^{ab}	188^{ab}	186^{abc}	183^{ab}	180^{abc}	180^{ab}
Depression	0	Low	194^{ab}	194^{ab}	194^{a}	194^{ab}	194^{ab}	191^{ab}	194^{ab}	194^{ab}
Depression	Low	Low	180^{abc}	180^{abc}	180^{ab}	180^{ab}	180^{abc}	178^{ab}	180^{abc}	178^{abc}
Depression	High	Low	175^{abc}	178^{abc}	178^{ab}	178^{abc}	178^{abc}	175^{abc}	172^{abcd}	170^{abcd}
Depression	0	High	172^{abcd}	172^{abc}	172^{abc}	172^{abcd}	172^{abcd}	172^{abc}	167^{abcde}	170^{abcd}
Depression	Low	High	143^{bcde}	143^{bcde}	140^{bcd}	140^{bcde}	143^{bcde}	140^{bcde}	140^{bcdef}	140^{bcde}
Depression	High	High	140^{bcde}	140^{bcdef}	137^{bcde}	140^{bcde}	137^{cde}	137^{bcde}	137^{cdef}	137^{bcde}
Hilltop	0	0	207^{a}	207^{a}	207^{a}	205^{a}	207^{a}	205^{a}	205^{a}	202^{a}
Hilltop	Low	0	164^{abcd}	170^{abc}	164^{abc}	164^{abcd}	164^{abcd}	164^{abcd}	161^{abcde}	164^{abcd}
Hilltop	High	0	75^{fg}	86^{fg}	86^{ef}	102^{ef}	89^{ef}	89^{ef}	91^{fg}	91^{ef}
Hilltop	0	Low	199^{ab}	199^{a}	199^{a}	199^{a}	199^{a}	191^{ab}	188^{abc}	191^{ab}
Hilltop	Low	Low	164^{abcd}	167^{abcd}	167^{abc}	167^{abcd}	167^{abcd}	159^{abcd}	156^{abcde}	159^{abcd}
Hilltop	High	Low	126^{cdef}	126^{cdef}	124^{cde}	121^{cde}	121^{de}	121^{cde}	121^{def}	118^{cde}
Hilltop	0	High	110^{defg}	113^{def}	121^{cde}	118^{de}	118^{de}	116^{de}	116^{ef}	116^{de}
Hilltop	Low	High	89^{efg}	89^{efg}	89^{def}	91^{ef}	89^{ef}	89^{ef}	86^{fg}	91^{ef}
Hilltop	High	High	48^{g}	51^{g}	54^{f}	54^{f}	54^{f}	54^{f}	54^{g}	54^{f}

$^{a\text{-}g}$ Means within the same column followed by the same letter grouping are not significantly different $P < 0.05$

Appendix E

Canola plant stand as percentage of maximum plant stand over time as affected by seed-placed MAP and AS on soil collected from a hilltop and depression area in a field near Nesbitt, MB (Chapter 3)

Table E.1a Canola emergence as a percentage of maximum plant stand with various fertilizer treatments on soils from different landscape positions from the Nesbitt, MB site at 0-12 days after emergence

			Days after emergence						
Landscape position	AS rate	MAP rate	0	2	4	6	8	10	12
Depression	0	0	92	94	96	100	100	97	100
Depression	Low	0	87	94	96	99	99	100	99
Depression	High	0	61	74	83	90	94	97	100
Depression	0	Low	87	94	97	97	100	100	100
Depression	Low	Low	75	93	97	99	99	99	100
Depression	High	Low	67	94	94	95	97	98	97
Depression	0	High	61	84	92	92	95	97	100
Depression	Low	High	38	57	70	85	91	98	100
Depression	High	High	46	65	90	92	94	96	98
Hilltop	0	0	87	94	95	96	97	97	100
Hilltop	Low	0	33	51	71	79	87	94	95
Hilltop	High	0	16	29	32	32	39	47	53
Hilltop	0	Low	70	84	95	96	99	97	100
Hilltop	Low	Low	63	85	84	87	90	92	94
Hilltop	High	Low	36	57	68	74	89	94	98
Hilltop	0	High	24	40	53	62	71	87	87
Hilltop	Low	High	21	24	35	41	53	71	82
Hilltop	High	High	15	25	30	30	45	65	75

Table E.1b Canola emergence as a percentage of maximum plant stand with various fertilizer treatments on soils from different landscape positions from the Nesbitt, MB site at 14-28 days after emergence

			Days after emergence							
Landscape position	AS rate	MAP rate	14	16	18	20	22	24	26	28
Depression	0	0	100	100	100	100	100	99	97	100
Depression	Low	0	100	100	100	100	100	99	99	99
Depression	High	0	99	100	100	100	99	97	96	96
Depression	0	Low	100	100	100	100	100	99	100	100
Depression	Low	Low	99	99	99	99	99	97	99	97
Depression	High	Low	98	100	100	100	100	98	97	95
Depression	0	High	100	100	100	100	100	100	97	98
Depression	Low	High	100	100	98	98	100	98	98	98
Depression	High	High	100	100	98	100	98	98	98	98
Hilltop	0	0	100	100	100	99	100	99	99	97
Hilltop	Low	0	97	100	97	97	97	97	95	97
Hilltop	High	0	74	84	84	100	87	87	89	89
Hilltop	0	Low	100	100	100	100	100	96	95	96
Hilltop	Low	Low	98	100	100	100	100	95	94	95
Hilltop	High	Low	100	100	98	96	96	96	96	94
Hilltop	0	High	91	93	100	98	98	96	96	96
Hilltop	Low	High	97	97	97	100	97	97	94	100
Hilltop	High	High	90	95	100	100	100	100	100	100

Appendix F

Canola emergence as affected by monoammonium phosphate and ammonium sulphate on soil collected from a hilltop and depression area of a field near Nesbitt, MB

Soil collected from the hilltop

Soil collected from the depression

0 **20** **40 kg P_2O_5 ha^{-1}**

Figure F.1 Effect of 0, 20 and 40 kg P_2O_5 ha^{-1} seed-placed monoammonium phosphate on canola plant stand in soil from a hilltop and depression near Nesbitt, MB

Soil collected from the hilltop

Soil collected from the depression

0 **9** **18 kg S ha^{-1}**

Figure F.2 Effect of 0, 9 and 18 kg S ha^{-1} seed-placed ammonium sulphate on canola plant stand in soil from a hilltop and depression near Nesbitt, MB