Phosphorus Beneficial Management Practices for Corn Production in Manitoba

by

Magdalena Rogalsky

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

MASTER OF SCIENCE

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba

1. ABSTRACT

Two phosphorus (P) fertilization studies were conducted for two field seasons to assess the effects of starter fertilizer on early corn plant growth, maturity, grain yield and grain moisture at harvest. The first part of the project, a crop rotation study, evaluated corn response to spring side banded P and Zn fertilizer when corn followed canola versus soybean. Treatments included a control (no starter) and two rates of P (30 and 60 kg P_2O_5 ha^{-1}) in the form of monoammonium phosphate (MAP, 11-52-0) or MicroEssentials® SZ (MESZn, 12-40-0-10-1) side banded (5 cm to the side and 2.5 cm below the seed) during corn planting in the spring of 2015 and 2016. Preceding crop did not have any influence on mycorrhizal colonization of corn roots (total, arbuscular, hyphal, vesicular). However, application of P suppressed total and arbuscular colonization of corn roots by 5 and 4% respectively, relative to the unfertilized control. Side banded fertilizer increased early season biomass by up to 110% compared to the unfertilized control, with the largest increases in corn following canola. Concentration and uptake of P in early season biomass increased as the P rate increased, and was greatest for the high rate of MAP and MESZn treatments. Zinc concentrations in plant tissue were highest for the unfertilized control and MESZn treatments, regardless of the preceding crop. Zinc uptake was significantly greater with application of starter fertilizer compared to the unfertilized control, especially in corn grown after canola. Silking date was advanced by 3-7 days with application of starter fertilizers. At harvest, all starter fertilizer treatments reduced grain moisture by 2-3% in corn

following canola only, and there was a 10% yield increase in grain yield with the high rate of MAP compared to the control, regardless of preceding crop.

The second part of the project, a residue management study, evaluated corn response to fall banded and spring side banded P fertilizer in strip-tillage and conventional tillage. Treatments included a control (no P), two rates of P (30 and 60 kg P_2O_5 ha^{-1}) in the form of MAP, applied either in the fall as a deep band (10-13 cm deep) with a strip-till unit or in the spring as a side band with a corn planter. At Carman in 2015 and 2016, spring side banded P treatments increased early season biomass by up to 103% compared to the unfertilized controls. Spring side banded P treatments consistently increased early season P concentration in plant tissue and P uptake at all site-years, relative to the unfertilized control. Banded P treatments reduced days to silking by 2-3 d compared to the unfertilized control. At harvest, banded P treatments reduced moisture by 1-2 g kg^{-1} at both site-years in 2016. Spring side band P treatments increased grain yield by an average of 467 kg ha^{-1} relative to the unfertilized control and out-yielded the fall deep banded treatments by 470 kg ha^{-1}, regardless of the tillage treatment.

2. ACKNOWLEDGMENTS

I would like to thank all the wonderful people that have helped me and encouraged me throughout my program. First and foremost, I would like to thank my husband, Mike for his support and understanding and for always lending words of reassurance and motivation.

Second, I would like to thank my supervisor, Dr. Don Flaten. I would not be where I am today if it wasn't for your encouragement, knowledge, fellowship and forever memorable teaching moments. Completing my thesis under your supervision has been and always will be an extremely valuable experience that was also fun and enjoyable!

Big thanks to my Brazilian agronomist, Gustavo Bardella for your patience, help, support and always educational trips out to the field. Thank you for helping me "survive" the initial years of my program and for your friendship. I would also like to thank John Heard for all your advice, shared experiences, and for having faith in this city girl while introducing me to producers. Thank you for your support with field activities and for being my "corn guru".

I would like to thank my supervising committee members, Dr. Mario Tenuta and Dr. Yvonne Lawley for your very much appreciated expertise and contributions to my learning experience. Thank you for your practical and always helpful suggestions and comments. Thank you to Dr. Francis Zvomuya for your indispensible help with statistical analysis.

I would like to thank my summer students, Megan Bourns, Matheus Castello and Thomas Cuddy for your exceptional work ethic and care with field and lab work. Thank you to the Plant Science Department crew for all of your help with equipment operation and field work.

Thank you to the technical and administrative staff at the Soil Science Department, Tim Stem, Lynda Closson, Amy Mangin, Trevor Fraser and Anthony Buckley for your patience and help.

I would like to thank Curtis Cavers (CMCDC), Alvin Iverson and Jim Dunn (University of Manitoba Research Station), Brian Hellegards (Richardson Pioneer) and Plateau Sands for your assistance and support with site set-up and for allowing me to have a positive field experience.

Thank you to Manitoba Corn Growers Association, Canada-Manitoba GF2 Program, Western Grains Research Foundation, Agrium, Mosaic and Western Economic Diversification Canada for providing the funding to make this project possible.

Thank you to my family for their encouragement, support, love and care during my program.

3. 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 of literature. Chapter 2 contains a manuscript for the crop rotation study, conducted at Stephenfield, MB (Plateau Sands commercial field) and Carman, MB (University of Manitoba Research Station) in 2014-15, and Portage la Prairie, MB (Canada-Manitoba Crop Diversification Centre) and Carman, MB (University of Manitoba Research Station) in 2015-16. The data from the Portage la Prairie 2016 site was excluded from Chapter 2 due to crop damage by flooding. Chapter 3 contains a manuscript for the residue management study, conducted at Carman, MB (University of Manitoba Research Station) and Portage, MB (Canada-Manitoba Crop Diversification Centre) in 2014-15, and 2015-16. I was responsible for managing all above sites and performing the statistical analysis of the field data collected.

Chapters 2 and 3 from this thesis will be submitted to the Canadian Journal of Soil Science; therefore, the reference style of this journal will be used throughout the thesis.

4. TABLE OF CONTENTS

5. LIST OF TABLES

6. LIST OF FIGURES

1. INTRODUCTION

Normal plant growth requires essential nutrients such as phosphorus (P) and zinc (Zn), and when these are not present in adequate amounts, crop nutrient deficiencies arise (Soltangheisi et al. 2013). Phosphorus is critical for many plant functions including energy storage and transfer, photosynthesis and respiration, cell division and enlargement, early root growth and is an essential component of DNA and RNA. Therefore, deficiency symptoms are often associated with restricted growth and development, negatively affecting structure, maturity, seed yield and crop productivity (Havlin et al. 2004). In corn, visual symptoms of P deficiency generally appear at the 3- to 6-leaf growth stage as a purple leaf colouration (Bittman et al. 2000).

In contrast, zinc is a micronutrient that acts as a functional, structural or regulatory cofactor and is involved in many enzymatic activities (Sutradhar et al. 2016) as well as synthesis of tryptophane, important for production of plant growth hormones (Havlin et al. 2004). Zinc deficiency leads to stunted crop growth, poor root development, small leaves and shortening of internodes and delayed plant maturity which can sufficiently limit yield (Havlin et al. 2004). In corn, visual symptoms of Zn deficiency appear as a “broad band of white to yellowish-white tissue on both sides of the leaf midrib” (Camberato and Maloney 2012). Due to the limited mobility of these two essential nutrients (McGonigle et al. 2011), in addition to corn’s susceptibility to low plant-available levels of P and Zn, fertilizer applications of P and Zn near the seed row may be necessary to enable adequate uptake at early stages of development.

Starter fertilizer is commonly used in corn production to improve early season growth (Bermudez and Mallarino 2002). Enhanced development of emerging seedlings and rapid crop establishment are desirable due to their positive influence on final yield (Beegle et al. 2007). Starter fertilizer is fertilizer that is placed in close proximity to the seed in a readily available form, at the time of planting (Hergert et al. 2012). This allows developing seedling roots to quickly obtain immobile nutrients such as P and Zn (Beegle et al. 2007).

Positional and chemical availability of nutrients close to the seed in the early-stages of growth may further result in accelerated crop maturity, and ultimately higher yield (Beegle et al. 2007). Recommended placement of starter fertilizer for corn is 2” beside and 2” below the seed (Bittman et al. 2000), as a “pop-up” application in the seedrow (Beegle et al. 2007). Banding P is an agronomically efficient and environmentally sustainable placement when compared to broadcast applications (Heard et al. 2014). Placement near the seed provides excellent access to nutrients for root uptake, especially soon after germination when cool soil conditions often limit nutrient mineralization and root development (Jokela 1992). Other benefits of banding include reduced soil to fertilizer contact, which translates into less P fixation and retention, and reduction in surface runoff losses (Heard et al. 2014). Ultimately, the goal of starter fertilizer use is to apply it when it is profitable and environmentally appropriate, in production systems where beneficial response to these treatments can be observed (Bundy and Andraski 1999).

Generally, nutrients that are included in starter fertilizer are P and nitrogen (N) and in some cases Zn may be added if soil Zn concentrations are below critical threshold for corn deficiency (Beegle et al. 2007; Hergert et al. 2012). However, in a study conducted by Stewart (2012), the inclusion of Zn in starter fertilizer blends did not produce yield responses greater than that of MAP (11-52-0) alone.

Although corn is one of the most responsive crops to starter fertilizer, application of starter should complement crop rotational decisions that impact nutrition via arbuscular mycorrhizal fungi (AMF) associations. Arbuscular mycorrhizal fungi form a symbiotic relationship with plant roots (Monreal et al. 2011), providing crops with a very effective pathway for acquiring soil nutrients (Smith et al. 2011). As most commercial crops are mycorrhizal, AMF is present in most soils (Miller 2000), and functions by increasing the effective zone of exploration, enhancing P and Zn uptake (Bittman et al. 2006). This effect of root colonization by AMF can be best observed when crops are grown in infertile and nutrient-deficient soils (Havlin et al. 2004) and is especially important when young corn plant roots, on their own, are incapable of acquiring sufficient nutrients to satisfy overall crop demand (Bittman et al. 2006).

Juvenile corn plants are highly responsive to early season absorption of P and Zn (Miller 2000), and will benefit from colonization by AMF, which improves early nutrition and contributes to an early growth advantage (Koide and Peoples 2012). Enhanced early growth results in early maturity, which often translates into greater grain yields and dry matter content (Bittman et al. 2006). Therefore, agricultural management practices capable of altering AMF populations and effectiveness may have an impact on final yield (Gavito and Miller 1998a). Under conditions where AMF quantity and quality is reduced, fertilizers may be needed to supply adequate amounts of nutrients to corn (Sutradhar et al. 2016). Studies conducted in coastal British Columbia assessed corn response with varying levels of AMF colonization to low rates of starter P and concluded that poorly colonized corn showed greater degree of P deficiency at the 6-leaf stage. However, increasingly greater quantities of starter fertilizer reduced the purpling symptoms associated with low AMF colonization of corn roots (Bittman et al. 2006).

Therefore, response to starter fertilizer is more likely to occur when corn is planted into soils where activity of arbuscular mycorrhizal fungi colonization is impeded (Hergert et al. 2012).

Conditions that may reduce AMF inoculum in soil and subsequent colonization include fallow, soil disturbance and the presence of non-mycorrhizal crop species in the rotation (Koide and Peoples 2012). One of the important non-mycorrhizal crops grown in western Canada is canola (Monreal et al. 2011). Therefore, growth of corn (*Zea mays* L.) following canola may be hampered by lack of AMF, reducing early season growth and uptake of P and Zn (McGonigle et al. 2011). As mentioned previously, corn is highly responsive to early absorption of P; therefore, inadequate concentrations at the 4- to 5- leaf stages can reduce yield (Gavito and Miller 1998b; Koide and Peoples 2012). In order to further assess the importance of AMF in corn nutrition and grain yield, Miller (2000) established canola in blocks of disturbed soil and found that when corn followed canola, early season nutrient absorption was reduced as mycorrhizal development and consequent colonization of corn roots was delayed. Bittman et al. (2000) also determined that cropping practices, such as fallow in the year prior to corn production caused stunting and purple colouration of corn at the 3- to 6-leaf stages, due to early season P deficiency. This is of particular importance since corn, under many circumstances, depends on AMF hyphal networks for increased spatial exploitation of the soil and a substantial fraction of its nutrient uptake (Smith et al. 2011). Therefore, management practices that reduce mycorrhizal symbiosis may have a negative impact on corn early season nutrition, specifically for P and Zn (McGonigle et al. 2011). Generally, crop rotation should avoid corn after canola or fallow; however, if this rotation is practiced, providing adequate nutrients with appropriate fertilization may allow for improved production (McGonigle et al. 2011).

Strip-till is an emerging residue management system where the use of starter fertilizer can also produce a positive response in row crops (Nowatzki et al. 2011). Strip-till systems incorporate the soil and water conservation benefits of no-till systems and the improved seedbed conditions of conventional tillage systems (Fernández and Schaefer 2012). However, the timing of the strip-till operation may vary. For example, in areas such as Manitoba where the growing season is short, fall strip-tillage is often preferred because it allows for the fastest soil warm-up in the spring and best seed-to-soil contact (Nowatzki et al. 2011). Strip-till is a suitable system for corn production because it provides good seedbed conditions for planting, promoting seed germination and emergence (Vyn and Raimbault 1992). Other advantages include reduced soil erosion and carbon release into the atmosphere, increased water infiltration and conservation (Nowatzki et al. 2011). Additionally, when compared to conventional tillage systems, strip-till decreases the overall area of seedbed preparation normally associated with conventional tillage by leaving a greater amount of residue on the surface, reducing operation costs (less energy, fuel, labour) (Vyn and Raimbault 1992).

Consequently, cool soil conditions at the time of planting and early stages of growth and development are associated with many conservation tillage systems, and may lead to decreased uptake of nutrients, including P (Osborne 2005). Planting corn in high residue conditions, including strip-till systems creates a greater risk of cool soil temperatures which may lead to development of P deficiency symptoms at the early stages of development due to reduced rate of root growth and P uptake (Gordon et al. 1997; Bittman et al. 2006; Gordon and Pierzynski 2006). Delayed early growth due to inadequate availability of nutrients in cool soils may lead to overall reductions in grain yield (Bermudez and Mallarino 2002). These effects are more likely to occur in strip-till and no-till corn rather than corn planted under conventional tillage (Bermudez and Mallarino 2002).

Therefore, under conservation tillage conditions, application of starter fertilizers, especially P, can improve early season crop development, decrease grain moisture content at harvest and increase grain yield of corn (Bundy and Andraski 1999). Osborne (2005) evaluated corn yield response to starter fertilizer in conventional tillage and fall strip-tillage and found that corn yield increased, even on soils with high levels of P fertility, regardless of the type of residue management. However, other studies have found that response to starter fertilizers was greatest under environmental conditions where cool soils limit early plant development and where P fertility was below optimum levels for corn (Gordon et al. 1997; Bermudez and Mallarino 2002; Mallarino et al. 2011).

While strip-till has a minimal effect on soil disturbance, conventional tillage operations impose high levels of soil disturbance (Landry et al. 2008), which can have negative effects on AMF quantity and colonization (Koide and Peoples 2012). Conventional tillage leads to physical disruption of roots and extraradical mycelium, while strip-tillage creates conditions conducive to AMF over-winter survival (Landry et al. 2008). Presence of viable hyphae in the spring allows for rapid corn root colonization, which is important for meeting the early season nutrient requirements of corn (Miller 2000). McGonigle and Miller (1993) compared conventional tillage and no-till disturbance levels and their effect on mycorrhizal colonization and shoot P concentration in juvenile corn plants. The results of the study showed an increase in shoot P concentration at the 5- to 6-leaf stage in the least disturbed treatments when compared with the most disturbed, conventional treatments. Application of starter fertilizers in conventional tillage and to a lesser extent strip-till system, in close proximity to the seed in a readily available form (Hergert et al. 2012) may improve P absorption for poorly colonized corn (Bittman et al. 2006).

Overall, the goal of starter fertilizer application is economic profitability and beneficial response to these treatments in production systems (Bundy and Andraski 1999). Therefore, optimizing placement of starter P in strip-till systems is of great interest (Randall and Vetsch 2008) since starter P is commonly recommended for corn production (Jokela 1992). Currently, subsurface application of P fertilizers is recommended to reduce potential losses and stratification of P at the soil surface (Randall and Vetsch 2008). In a study conducted by Mallarino et al. (2011), placement of starter fertilizer in a 2” by 2” band in a strip-till system showed substantially greater yield response when compared to placement only below the seed. Consequently, the recommended placement for starter fertilizer in strip-till corn is in a 2” by 2” band at planting (Heard et al. 2014) as this method provides readily available nutrients to the young roots and is less susceptible to runoff losses (Jokela 1992).

Positional and chemical advantages for banded P compared to broadcast P are well documented in literature (Kaiser et al. 2005; Osborne 2005; Randall and Vetsch 2008; Mallarino et al. 2011). However, lack of planter capability for banding fertilizer in or near the seed row frequently creates limitations for suitable fertilizer placement in a strip-till system for corn production. . Albeit the use of precision navigation technology has been growing in popularity for both planting and strip-till equipment in recent years (Fernández and Schaefer 2012). Real Time Kinematic (RTK) GPS technology allows for better positioning accuracy and the ability to place and mark fertilizer bands in the fall and then plant seed rows in or near the same location as the fertilizer bands, improving efficiency and plant fertilizer use (Nowatzki et al. 2011). Currently in Manitoba, a large percentage of farmers apply their fertilizer in the fall prior to corn planting, while only few have planter capability for banding starter fertilizer at the beginning of the season.

Although soil conditions are an important factor when evaluating corn response to starter fertilizer, application of starter fertilizer may only be economical for some corn hybrids (Bermudez and Mallarino 2002). Differences in response may be attributed to morphological and physiological root characteristics (Gordon et al. 1997). Differences in these characteristics may influence the amount nutrient uptake by individual corn genotypes (Gordon et al. 1997). A total of five corn hybrids were evaluated by Gordon et al. (1997) from the spring of 1993 to the fall of 1995 and four corn hybrids were evaluated by Gordon and Pierzynski (2006) from the spring of 1996 to the fall of 1998. Gordon et al. (1997) used a starter fertilizer blend for ICI 8599, Pioneer 3563, DeKalb 636, DeKalb 591 that included N and P as ammonium polyphosphate (APP,10-34-0) and urea-ammonium nitrate (UAN, 28-0-0) combined, banded 2” below and 2” beside the seed. When averaged over the 3 years of the experiment, starter fertilizer increased the yields of Pioneer 3346 and DeKalb 636 by 14 bu ac^{-1}. Starter fertilizer improved grain yield of DeKalb 591 significantly in 2 of the 3 years of the study. However, yields of IC1 8599 and Pioneer 3563 were not affected by starter fertilizer in any year of the experiment (Gordon et al. 1997). Gordon and Pierzynski (2006) used a more comprehensive starter fertilizer blend, including N, P, K, S and Zn at variable rates and elemental composition, which was banded 2” below and 2” beside the seed. Nitrogen and P starters decreased grain-moisture content at harvest and increased total P uptake of Pioneer 3346 and DeKalb 591. Addition of starter fertilizer had no influence on grain yield or rooting depth of Pioneer 3563 and DeKalb 646; however, starter fertilizer increased both of these measurements for Pioneer 3346 and DeKalb 591. Difference in responses of each hybrid to starter fertilizer blends appeared to be due to rooting characteristics and patterns, with some hybrids capable of continuous root development and nutrient uptake even under unfavourable conditions (Gordon and Pierzynski 2006). Results of these experiments demonstrate the need for careful selection of corn hybrids for evaluating the benefits of starter fertilizer.

The effects of starter fertilizer management for corn have not been studied extensively in Manitoba, where the acreage of corn has traditionally been relatively small, due to our short growing season. However, interest in grain corn production in Manitoba is increasing. Given these trends as well as Manitoba's large acreage of canola production, the objectives for the crop rotation study were to evaluate corn yield, growth and nutrient uptake response to side banded P and Zn fertilizers when corn follows canola vs. soybean. Given Manitoba farmers' longstanding dedication to conservation tillage, the objectives of the residue management study were to evaluate corn response to phosphorus rate, placement and timing in strip-tillage and conventional tillage. In both studies, we hypothesized that the addition of starter fertilizer would improve early corn development, hasten maturity and increase yields and that those improvements would be especially substantial in corn following canola or corn grown in strip-tillage.

2. RESPONSE TO SIDE BANDED PHOSPHORUS AND ZINC FERTILIZER FOR CORN GROWN AFTER CANOLA

Keywords: *Zea mays* L., phosphorus, zinc, canola, side band, early season biomass, arbuscular mycorrhizal fungi, plant height, maturity, grain moisture, grain yield

2.1 Abstract

Short growing seasons and cold soils at planting present Manitoba farmers with incentives to use starter fertilizer for grain corn (*Zea mays* L.) production. A crop rotation study conducted for two corn test crop years assessed the effects of starter fertilizer on early corn growth, maturity, grain moisture and grain yield at harvest when corn followed canola versus soybean. Treatments included a control (no starter) and two rates of P (30 and 60 kg P_2O_5 ha^{-1}) as monoammonium phosphate (MAP, 11-52-0) or MicroEssentials® SZ (MESZn, 12-40-0-10-1) side banded (5 cm to the side and 2.5 cm below the seed) at planting. Preceding crop did not have any influence on mycorrhizal colonization of corn roots. Side banded fertilizer increased early season biomass by 30-110% compared to the unfertilized control. Phosphorus concentration and uptake in early season biomass increased as the P rate increased. Zinc concentrations were greatest for the unfertilized control and MESZn treatments, while Zn uptake was significantly greater with application of starter fertilizer compared to the unfertilized control. Starter P advanced silking date by 2-7 days relative to the unfertilized control. Starter P reduced grain moisture by 2-3% in corn after canola, and high rate of MAP increased grain yield by 770 kg ha^{-1} compared to the unfertilized control.

2.2 Introduction

In 2016, Canadian farmers reported planting 3.3 million acres of grain corn (*Zea mays* L), a 1.7% increase from the previous year. That same year, in Manitoba alone, grain corn acreage increased by 30% compared to acreage reported in 2015 (Statistics Canada 2016). Being located on the northern fringes of the Northern Great Plains, Manitoba has a relatively short growing season (approximately 135 days from beginning of May until mid September). Therefore, timely planting of corn is important, especially for full-season corn hybrids that need to reach maturity before the killing freeze in the fall. Unfortunately, early spring planting is also associated with cold soils that reduce root growth, nutrient mobility and mineralization (Beegle et al. 2007). Due to these environmental conditions, it is very important to manage P and Zn fertilization carefully, to reduce cropping risk, improve agronomic production and increase profitability.

Phosphorus is an essential macronutrient required for corn production as it is critical for many biochemical reactions and serves as a structural component of DNA and RNA (Havlin et al. 2004; Grant 2012). In contrast, zinc is a micronutrient that acts as a functional, structural or regulatory cofactor that is involved in many enzymatic activities and synthesis of tryptophane, important for production of plant growth hormones needed for optimum growth and maximum yield (Havlin et al. 2004; Sutradhar et al. 2016). Symptoms of P deficiency can be observed in young corn leaves (V3-V4 growth stage) as a purpling colouration (Cobbina and Miller 1987), delayed leaf emergence and subsequent reductions in dry matter and grain yield. Alternatively, white to yellow chlorosis (V4-V6 growth stage) in areas of leaf close to the stalk indicates Zn deficiency (Carsky and Reid 1990; Camberato and Maloney 2012) and in cases of severe deficiency, internodes shorten, resulting in stunted crop growth and delayed plant maturity (Alloway 2004; Havlin et al. 2004). Zinc deficiency is most prevalent "… on high pH, low organic matter soils in years with cold, wet springs" (Manitoba Corn Growers Association 2014). Due to limited mobility of P and Zn (McGonigle et al. 2011), implementing beneficial management practices that facilitate adequate uptake of these nutrients at the early stages of development is important, given corn's high sensitivity to P and Zn deficiency.

Some of the most important considerations for improved P and Zn management practices are crop rotational decisions that impact nutrition via arbuscular mycorrhizal fungi (AMF) associations. Arbuscular mycorrhizal fungi form symbiotic relationships with up to 80% of terrestrial plant species, including most commercial crops; therefore, AMF are present in most agricultural soils (Miller 2000). The host plant benefits from enhanced uptake of P and Zn via extensive hyphal networks in soil and the fungi benefit by having access to plant-assimilated carbon (An et al. 2010; Monreal et al. 2011). The effect of AMF colonization is often greatest in infertile and nutrient-deficient soils (Havlin et al. 2004), although the level of colonization varies among host plant genera from non-colonization in *Brassica* to 50-70% in *Zea* (An et al. 2010). Canola (*Brassica napus*) is an important, non-mycorrhizal crop grown in Western Canada, and presence of this non-mycorrhizal crop in the rotation may reduce AMF inoculum in soil and hamper subsequent colonization of corn (Koide and Peoples 2012). This is especially important since juvenile corn plants are highly responsive to early season absorption of P and Zn and benefit from AMF colonization, particularly at the early stages of growth during which young corn roots are incapable of acquiring sufficient nutrients to satisfy overall crop demand (Miller 2000; Bittman et al. 2006; Koide and Peoples 2012). Therefore, reductions in corn mycorrhizal symbiosis may lead to delayed early season growth and development (due to inadequate absorption of P and Zn) and potentially cause reductions in yield (Gavito and Miller 1998a). Under conditions where AMF quantity and quality is reduced, such as cropping with canola or fallow, fertilizers may be needed to allow for improved production and nutrient uptake early in the growing season (Kaiser et al. 2015).

To complement rotational decisions, consideration should be given to optimized P and Zn fertilization management practices, which address plant nutrition via right placement, right rate, right timing and right source of fertilizer. Application of starter fertilizer is a common practice in corn production, where low rates of fertilizer are placed in-furrow or side banded (banded 5 cm to the side and 5 cm below the seed) (Bermudez and Mallarino 2002; Kaiser et al. 2016). Starter fertilizer banded 5 cm to the side and below the seed row offers access to P and Zn in a readily available form, early in the season, at a time where root growth and plant uptake are limited (Lu and Miller 1993; Beegle et al. 2007; Kaiser et al. 2016). Further, side band placement reduces soil to fertilizer contact and is less susceptible to surface runoff losses compared to broadcast applications (Jokela 1992; Heard et al. 2014).

Banding and seedrow placement of starter fertilizer has been shown to substantially increase early season growth and plant height (Bundy and Andraski 1999; Bermudez and Mallarino 2002; Kaiser et al. 2005; Roth et al. 2006; Wortmann et al. 2006; Kim et al. 2013), advance maturity (Bullock et al. 1993; Cromley et al. 2006), reduce kernel moisture at harvest (Mascagni and Boquet 1996) and, to a lesser extent, increase grain yields (Jokela 1992; Bundy and Andraski 1999; Bermudez and Mallarino 2002; Vetsch and Randall 2002). These effects are especially visible under conditions where AMF inoculation has been reduced (Bittman et al. 2006) or in areas where cool soil conditions at planting can restrict uptake of P and Zn early in the growing season (Kaiser et al. 2015, 2016).

Generally, nutrients that are included in starter fertilizer are P and nitrogen (N); however, in some cases Zn may be added if soil test Zn concentrations are below critical threshold for corn deficiency (Beegle et al. 2007; Hergert et al. 2012). Many different fertilizers can be used, including ammonium sulphate (21-0-0-24S) and ammonium nitrate (34-0-0) for N starters, triple super phosphate (0-45-0) for P-only starter, monoammonium phosphate (11-52-0) for N-P starter and MicroEssentials® SZ (12-40-0 10S 1Zn) for N-P-S-Zn starter. MicroEssentials® SZ is a specialty product, developed by the Mosaic company that uniformly fuses all four nutrients (N, P, S and Zn) in each granule to improve plant access to all four nutrients and to ensure even distribution. However, starter fertilizer response is generally attributed mostly to the inclusion of P in the mixture due to the plant's large early season requirements for this essential nutrient (Randall and Hoeft 1988). Further, inclusion of Zn in starter blends does not always produce a yield advantage (Stewart 2012) or provide the intended economic benefit (Phair 2012) compared to MAP (11-52-0) alone. In cases where Zn fertilization does increase yields, the response varies with growing season and the gain is generally marginal (Mallarino and Webb 1995).

While nutrient composition may be an important factor in corn response to starter fertilizer, application may be economical only for select corn hybrids (Bermudez and Mallarino 2002). Differences in morphological and physiological root characteristics may impact nutrient uptake by individual corn genotypes and influence the effectiveness of starter fertilizer (Gordon et al. 1997). Such differences in response were observed by Teare and Wright (1990) where only 8 out of 21 tested corn hybrids consistently had a positive response to starter fertilizer, compared to several other hybrids that responded negatively to the same application. In Missouri, Cromley et al. (2006) showed no differences in yield response to side banded liquid starter fertilizer for all hybrids tested. In contrast, Mascagni and Boquet (1996) concluded that application of starter fertilizer reduced grain moisture at harvest and accelerated maturity across all hybrids and years. Consequently, economic implications need to be considered since the goal of starter fertilizer application is economic profitability and beneficial response to these treatments in production systems (Bundy and Andraski 1999).

As corn production in Manitoba expands, more opportunities for diverse crop rotations emerge along with interest in starter fertilizer use under our climatic conditions. However, given the large acreage of canola production in our province, growers may not always have the opportunity to avoid planting corn after canola. Since corn is one of the most responsive crops to starter fertilizer, especially when planted into cold soils where activity of AMF colonization is impeded, the objectives of this study were to evaluate corn yield, growth and nutrient uptake response to side banded P and Zn fertilizers when corn follows canola vs. soybean. We hypothesized that the addition of starter fertilizer would improve early corn development, hasten maturity and increase yields. Further, we also hypothesized that corn would be more responsive to P and Zn after canola than soybean due to a decrease in AMF colonization of corn roots following non-mycorrhizal canola crop.

2.3 Materials and Methods

2.3.1. Site Description and Characteristics

Preference was given to field sites with low to medium Olsen extractable soil test P ($\leq$15 mg kg^{-1}). To determine site suitability for the crop rotation study, 12 - 20 soil cores were collected in the spring of 2014 and 2015 from potential sites before the rotation crop or corn test years. Soil cores were divided into 0-15 and 15-60 cm depths and matching depths were combined into a composite sample. Each sample was sent to AgVise Laboratories (Northwood, ND, USA) for complete soil fertility analysis (0-15 cm depth: phosphorus, potassium, zinc, organic matter, calcium, magnesium, sodium, CEC, base saturation, iron, manganese, copper, boron; 15-60 cm depth: nitrogen, pH, salts, sulphur, carbonates, chloride). Phosphorus concentration was determined by sodium bicarbonate extraction (Olsen), zinc by DTPA, pH and salts determined by 1:1 soil:water ratio, nitrate concentration by cadmium reduction, carbonates by pressure method, organic matter by loss on ignition, exchangeable potassium by ammonium acetate and sulphur (sulphate) by the turbidometric method.

The four selected study sites included, Carman, MB (University of Manitoba's Ian N. Morrison Research Farm) (49°29' N, 98° 1' W, 2015) and (49°29' N, 98°2' W, 2016), Stephenfield, MB (commercial field site) (49°30' N, 98°15' W, 2015) and Portage la Prairie, MB (Canada-Manitoba Crop Diversification Centre) (49°57' N, 98°16' W, 2016). Unfortunately, in 2016, the Portage la Prairie site suffered from catastrophic midseason flooding and the data from this site has been excluded from this chapter and statistical analysis.

In the fall prior to the corn test crop year, 10 soil cores were collected (0-15 and 15-60 cm depths) at each site to determine basal rates of any additional nutrients, including potassium (K), sulphur (S) or micronutrients other than zinc (Zn) (Appendix A.2). Soil was sampled once more in the spring before planting corn at each site and 10 cores were collected at two depths (0-15 and 15-60 cm) from each replicate of each crop block. Soil samples were sent to AgVise Laboratories (Northwood, ND, USA) to measure residual nitrate-N and determine nitrogen (N) fertilizer requirements. Soil texture was determined using the pipette method to determine particle size (Carter and Gregorich 2008) and classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998). Soil phosphorus concentrations ranged from 6 to 19 mg kg^{-1} Olsen extractable P and Zn-DTPA concentrations ranged from 0.82

to 1.91 mg kg^{-1} DTPA-Zn at 0-15 cm depth (Table 2.1). Stephenfield 2015 was the only site where Zn concentrations were below the critical soil test threshold (1.0 mg kg^{-1}) for recommending Zn fertilizer application in corn (MAFRD 2007).

Table 2.1 Soil characteristics for each site-year, in spring prior to corn planting.

Site-Year	Soil Series[a]	Texture[b]	Particle Distribution			Soil Test[c]		
			Sand	Silt	Clay	P	Zn	pH
			g kg^{-1}			mg kg^{-1}		
Carman 2015	Denham	SL	760	80	160	19 (H)[d]	1.50	5.1
Stephenfield 2015	Long Plain	LFS	830	70	100	6 (L)	0.82	7.9
Carman 2016	Rignold	SCL	650	120	230	9 (L)	1.91	5.2

[a] Soil series information obtained from Detailed Soil Survey Maps and Reports (https://www.gov.mb.ca/agriculture/land/soil-survey/importance-of-soilsurvey-mb.html#detailed).
[b] Abbreviations for the texture classes are SL, sandy loam; LFS, loamy fine sand; SCL, sandy clay loam
[c] Concentrations at 0-15 cm depth; P, Olsen-bicarbonate; Zn, DTPA-Zn; pH, soil pH 1:1 soil/water.
[d] Level of agronomic P sufficiency in soil indicated by the letters L and H mean low and high, respectively (MAFRD 2007).

2.3.2. Preceding Crop Management and Site Preparation

In 2014 and 2015, canola and soybean were grown as preceding crops. Canola was seeded at 100 plants m^{-2} at 13-25 mm depth. Canola varieties included Roundup Ready® or Liberty Link® canola. A Roundup Ready® soybean variety was planted at 50 plants m^{-2} at 25 mm depth. Prior to planting, soybean seed was treated with Cruiser Maxx Vibrance® seed treatment in 2014 and Acceleron® seed treatment in 2015 and granular inoculant was applied in-furrow at a rate of 22 kg ha^{-1} both years. Recommended herbicides for weed control in canola and soybean crops were applied using a bike sprayer (Appendix A.5). Midseason plant counts were conducted at 4 wk after planting and samples of the canola and soybean grain were collected for yield determination (Appendix A.1). The producer harvested the remainder of the crop and plots were tilled in fall, using a tandem disk at all sites to anchor canola and soybean crop residue in their respective blocks and to incorporate basal rates of K fertilizer, where necessary. Additional spring tillage was done prior to planting at Carman 2015, whereas pre-plant burnoff herbicide was applied at Stephenfield 2015 and Carman 2016 (Appendix A.5).

2.3.3. Experimental Design and Treatments

The experimental design was a randomized split-block design with four replicates, with the preceding crops of canola and soybean forming blocks that were subdivided for the starter fertilizer treatments. The starter fertilizer treatments consisted of a control (no starter) and rates of either 30 or 60 kg P_2O_5 ha^{-1} in the form of monoammonium phosphate (MAP, 11-52-0) or MicroEssentials® SZ (MESZn, 12-40-0-10-1) side banded (SB) (5 cm to the side and 2.5 cm below the seed) during corn planting in the spring. Even though ammonium sulphate (21-0-0-24) was added as a basal application at sites where soil tests indicated a risk of S deficiency, additional ammonium sulphate was included in the MAP treatments in order to compensate for the total additional amount of sulphur (S) in the MicroEssentials® SZ product. Albeit, 50% of the S in MESZn is in the elemental form, which must oxidize before it becomes plant available and the other 50% of the S is in the plant available form of sulphate. The treatments are summarized as follows:

T1) Control (No starter; no added S beyond basal treatment)		
T2) 30 kg P_2O_5 and 7.5 kg S ha^{-1}	MAP+AS	SB
T3) 60 kg P_2O_5 and 15 kg S ha^{-1}	MAP+AS	SB
T4) 30 kg P_2O_5 and 7.5 kg S and 0.75 kg Zn ha^{-1}	MESZn	SB
T5) 60 kg P_2O_5 and 15 kg S and 1.5 kg Zn ha^{-1}	MESZn	SB

Nitrogen fertilizer was broadcasted in the spring as SUPERU® in 2015 and AGROTAIN® treated urea in 2016 prior to corn planting and incorporated to a small degree with the corn planter. Sufficient N was applied to each plot to reach a target N supply of 250 kg N ha^{-1}, taking into account N in the starter fertilizer treatments and soil test nitrate-N concentrations. Corn hybrid Dekalb 26-28RIB Genuity® VTDoublePRO® (76-d RM) was planted 40-45 mm deep at 80,942 seeds ha^{-1} in 76-cm-wide rows using a four-row planter (John Deere 1755 4R drawn planter) at a speed of 3.2 km hr^{-1} in mid to late May (Table 2.2). There were several considerations for selecting the corn hybrid for this study. The corn hybrid was chosen to represent a hybrid commonly grown by Manitoba farmers. Further, the hybrid was chosen based on corn heat units and the ability of the hybrid to reach maturity prior to the fall frost in the study area. In addition, commercial market availability of the hybrid for the duration of the study and yield potential were also considered. Each four-row plot measured 3 by 8 m. Appropriate herbicides were applied in the crop with a bike sprayer up to V4 growth stage and a backpack sprayer for the subsequent crop growth stages (Appendices A.4 and A.5).

Table 2.2 Summary of planting and harvest dates for corn test crop in 2015 and 2016

Site-Year	Planting Date	Harvest Date
Carman 2015	May 25/15	Oct. 15/15
Stephenfield 2015	May 26/15	Oct. 14/15
Carman 2016	May 12/16	Oct. 05/16[a]

[a] Hand harvested due to mid season wind damage and green snap.

2.3.4. Weather Conditions

Accumulated corn heat units (CHU) were sufficient at all site-years for the corn hybrid to reach physiological maturity (2150 CHU) (Table 2.3). Total recorded growing season precipitation was below the required amount by the crop, considering a 7519 kg ha^{-1} corn crop uses about 530 mm in an average year, with corn water-use being the highest during reproductive phases of silking and pollination (July-Aug.) (Manitoba Corn Growers Association 2014). At

Stephenfield 2015, recorded precipitation for the month of Aug. was 8 mm, creating water stress conditions during pollination, which can affect silk elongation. Additionally, this site has very coarse-textured soils, where moisture stress can be further aggravated by low levels of precipitation. Although the corn crop had additional access to stored soil water, an overall measure of spring available soil moisture at each site-year indicated a growing season water balance deficit (Appendix J).

Table 2.3 Maximum, minimum and average air temperature, corn heat units (CHU), monthly and total precipitation, during the 2015 and 2016 growing seasons at Carman and Stephenfield, Manitoba

Site-Year	Air Temperature				Precipitation					
	T_{max}	T_{min}	$T_{average}$	CHU_{total}	May	June	July	Aug.	Sep.	Total
	air temperature, C°				mm					
Carman 2015[a]	23.5	9.9	16.7	2708	7.6	75.3	109.3	47.3	42.0	297
Stephenfield 2015[b]	25.8	11.1	18.0	2613	20.0[c]	83.6[c]	105.4	8.1	26.9	264
Carman 2016[d]	22.9	10.4	16.7	2825	106.0	95.2	78.5	57.5	64.2	404

[a] Weather data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for Carman 2015 from May 25 to Oct. 15.
[b] Stephenfield weather data recorded between 2015 June 10 and 2015 Oct. 14 from a WatchDog 1000 Series Micro Station installed at the site on 2015 June 10.
[c] Prior to weather station installation, rainfall was recorded using a simple rain gauge from 2015 May 27 to 2015 June 09, and the recorded rainfall from June 01 – 09 was added to the totals recorded with the WatchDog weather station for that month.
[d] Weather data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for Carman 2016 from May 12 to Oct. 05.

2.3.5. Early season Crop Measurements

Roots were collected from the control (T1) and high rate of MESZn (T5) treatment plots at V4 (based on visible leaf collar). Three plants were selected at random from the two outside rows and dug up. Excess soil was removed from the roots in the field, and the roots were later gently hosed down with water. Each root sample was preserved in 95% ethanol. For each sample, a total of 60 fine root segments, 20-30 mm long were cleared in 10% KOH for 24 h at 60°C and then stained with Chlorazol Black E (Brundrett et al. 1984) to store in 50% glycerol solution. Mycorrhizal colonization was assessed using a line transect method as described by

McGonigle et al. (1990b). Arbuscular, hyphal and vesicular colonization were scored as three separate categories and the total percent colonization was calculated based on the presence of at least one of these structures (Gavito and Miller 1998a) from a total of 100 root intersections observed at 100 times magnification using a stereo microscope.

Early season biomass was collected by cutting 10 randomly selected plants at ground level from the two outside rows from each plot at V4 (based on visible leaf collar). Fresh samples were weighed and air-dried for a week. Biomass was then cut into smaller sections, oven dried at 60°C for 72 h, weighed, and ground to pass through a 1-mm screen.

Phosphorus and Zn concentration and uptake were determined for early season biomass collected at V4. Dried and ground samples were sent to AgVise Laboratories (Northwood, ND, USA) for nitric acid-peroxide digestion and P and Zn analysis by inductively couple plasma emission spectrometry. Plant P and Zn uptake were calculated from nutrient concentrations and oven-dried early season biomass weights.

Plant height was assessed by measuring from the ground to the extended tip of the most newly emerged leaf at V7 on 10 randomly selected plants from two middle rows of each plot.

2.3.6. Mid to Late Season Crop Measurements

The number of days from planting until the day when ≥50% of the plants in the two centre rows of each plot had reached the silking stage was recorded for each plot.

Late season cob moisture was assessed weekly, starting at dough (R4) stage until approximately one week prior to harvest. Moisture was measured using an Electrophysics® moisture meter with corn probe (Dutton, Ontario Model MT808C). Two readings were taken per cob, from six randomly selected cobs per plot. Final moisture reading was an average of 12 readings for each plot.

2.3.7. Late Season Crop Measurements

Grain yield and moisture content were determined by harvesting the two middle 8-m long rows from each plot using a plot combine (Wintersteiger Classic with HarvestMaster® Classic GrainGage system) in 2015. In 2016, strong winds at Carman on July 20 caused 45 to 67% of green snap in the corn plots (Appendix K.2a). Therefore, in that year, grain yield and moisture content were determined by selecting and hand-harvesting 32 corn cobs and stationary threshing with a plot combine. Corn cobs were collected from plants where intra-row and inter-row competition were regarded as typical for a corn stand not damaged by green snap (ie., cobs were collected from plants that had at least two undamaged plants on each side within a row and at least two undamaged plants in the two rows directly beside the sampled plant). For plants where two cobs developed, only the main cob was collected. Corn cobs were hand-harvested from each plot from an area equivalent to 4.05 m^2 (1/1000th of an acre) determined from plant stand counts at 4 wk following planting (Appendix B.1b). Grain yields in both corn test crop years were adjusted to 155 g kg^{-1} moisture.

2.3.8. Statistical Analysis

Glimmix Procedure in SAS 9.4 was used for statistical analyses (SAS Institute, Inc. 2016). Treatment and site-year were considered fixed effects and block (site-year), and crop × block (site-year) were considered random effects. Conformity of the data was tested using the Shapiro-Wilk Statistic and assumptions regarding data conformity were tested using Proc Univariate. The Glimmix Procedure corrected for unequal variances for site-years with missing data. The Tukey-

Kramer test was used to assign letter groupings for treatment least squares means (P<0.05). Silking date did not follow normal distribution and the datasets for this variable were transformed using the gamma distribution. Late season cob moisture was analyzed using compound symmetry (CS) structure for repeated measure analysis.

2.4. Results and Discussion

2.4.1. Arbuscular Mycorrhizal Fungi Colonization (V4)

Surprisingly, preceding crop did not significantly affect colonization of corn roots (total, arbuscular, hyphal, vesicular) in our experiment (Table 2.4a,b, Appendix B.3a,b). This lack of effect from the non-mycorrhizal canola crop is contrary to most studies (Gavito and Miller 1998a, 1998b; Bittman et al. 2006; Gao et al. 2010; McGonigle et al. 2011; Monreal et al. 2011). The lack of differences in AMF colonization in corn roots following different crop rotations might have been the result of environmental conditions during the three years of this study. Gao et al. (2010) reported that overall AMF colonization was not consistent between years, and canola effects were observed in only 2 out of 3 years in their study.

In our experiment, the inhibitory effect of canola on percent corn root colonization may have already disappeared by the V4 (visible leaf collar stage) growth stage. Although recent research in Manitoba (Brar et al. 2016) showed that hyphal colonization of corn roots was lower for corn after canola at the V6 stage when compared with corn following mycorrhizal crops, this effect was not visible at silking. Similarly, Gavito and Miller (1998a) reported differences in AMF colonization at the V3 leaf stage that persisted until the V6 stage, and disappeared by silking. Therefore, as the season progresses and the crop matures, detection of significant percent colonization differences among corn roots following different crop rotations may diminish, although in both cases that effect disappeared much later in the season compared to our study. It is also important to recognize that by simply noting the presence or absence of fungal structures using morphological features, we are limited in our assessment to simply quantify the extent to which these fungal structures are present or absent, rather than their density or activity (Faber et al. 1990). In addition, Biermann and Linderman (1981) concluded that the percent colonization method, such as the one used in our experiment, is less accurate than the root length colonization method and assessment of AMF percent colonization because the presence or absence of AMF morphological features in root segments overestimates the extent of colonization. The percent colonization method does not estimate the mean extent of colonization and consequently the root segments which were counted as positive may not have been mycorrhizal for their entire length, and those counted as non-mycorrhizal may have been colonized.

Therefore, with the above considerations, a measure of phosphate uptake may be a more direct measure of AMF activity because as the plant root systems enlarge, absolute fungal mass increases while percent infection remains constant (Biermann and Linderman 1981; Faber et al. 1990).

Addition of starter fertilizer suppressed total colonization (TC) and arbuscular colonization (AC) of corn roots at V4 (Table 2.4a,b). Similar results were obtained by McGonigle et al. (1990a) and Bittman et al. (2006), where P fertilization significantly reduced AMF colonization in sampled corn roots. This reduction in mycorrhizal association is due to improved P status of the roots, which limits exudation of signal molecules responsible for hyphal branching (Grant et al. 2005). However, in our experiment, all fertilizer treatments had high rates of TC and AC, and the overall degree of suppression was small, with absolute reductions of only

5% in TC and 4% in AC, regardless of the preceding crop. One reason for this modest effect of starter fertilizer on the corn root colonization might be the localized effect of banded P. Lu et al. (1994) reported that although proportion of corn root length colonized was lower in a fertilizer band, roots of the same plant growing outside the band were well colonized. Nevertheless, the high incidence of arbuscules (dominant form of colonization) in our study suggests active exchange of plant assimilated carbon for P even in the presence of fertilizer P.

Site-year affected hyphal (HC) and vesicular (VC) colonization (P=0.0244 and 0.0376, respectively, Appendix B.3a,b) with HC colonization at 16% at Carman 2015 and Stephenfield 2015, compared to 11% at Carman 2016. Vesicular colonization was low for all site-years; however, VC was significantly greater at Carman 2016 (6%) compared to Carman 2015 (3%), and there was no difference in colonization between Stephenfield 2015 and the other two site-years.

Table 2.4a Total mycorrhizal fungi colonization of corn roots at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				%			
Canola	0	0	0	Control (no starter)	64	65	66	65
	60	15	1.5	MESZn	54	56	63	58
Soybean	0	0	0	Control (no starter)	61	63	71	65
	60	15	1.5	MESZn	53	64	68	61
Canola					59	60	64	61
Soybean					57	63	70	63
	0	0	0	Control (no starter)	62	64	68	65*a*[c]
	60	15	1.5	MESZn	53	60	66	60*b*
Site-year					58	62	67	

ANOVA	Df	Pr>F
Fert	1	0.0094*
Crop	1	0.4017
Crop*Fert	1	0.4011
Site-year	2	0.1510
Site-year*Fert	2	0.3844
Site-year*Crop	2	0.4747
Site-year*Crop*Fert	2	0.5576
Coeff Var (C.V.)		15

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Table 2.4b Arbuscular colonization of corn roots at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				%			
Canola	0	0	0	Control (no starter)	59	62	63	61
	60	15	1.5	MESZn	48	52	61	54
Soybean	0	0	0	Control (no starter)	58	56	68	61
	60	15	1.5	MESZn	49	59	62	56
Canola					53	57	62	57
Soybean					54	57	65	59
	0	0	0	Control (no starter)	59	59	66	61*a*[c]
	60	15	1.5	MESZn	49	55	61	55*b*
Site-year					54	57	63	

ANOVA	df	Pr>F
Fert	1	0.0109*
Crop	1	0.6716
Crop*Fert	1	0.4188
Site-year	2	0.1142
Site-year*Fert	2	0.4258
Site-year*Crop	2	0.8784
Site-year*Crop*Fert	2	0.2535
Coeff Var (C.V.)		17

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

2.4.2. Early Season Biomass (V4)

The close proximity of starter fertilizer to the seed in the fertilized plots generally increased early season biomass (ESB) of corn at V4, compared to the unfertilized controls (Table 2.5). However, the ESB response was affected by a crop × fertilizer interaction. In corn after canola, all fertilized treatments substantially increased ESB by 85-110% compared to the unfertilized control. In contrast, the ESB response to starter fertilizer was much smaller in corn after soybean, where only three out of the four fertilized treatments (excluding the low rate of MESZn) increased ESB by 30-38% compared to the unfertilized control. Even though ESB was equivalent for all fertilized treatments in both rotations, the unfertilized corn after soybean had significantly more ESB (293 kg ha^{-1}) than corn after canola (190 kg ha^{-1}). Similarly, in Pennsylvania Roth et al. (2006) observed a substantial increase in early season biomass (123-118%) with starter P application compared to a no starter control. In Minnesota studies, Kaiser et al. (2015) observed more modest increases in early season corn plant growth (15%) with the addition of low rates of liquid in-furrow P.

Wortmann et al. (2006) observed greater early response with soil test P (STP) of 15 mg kg^{-1} (Bray-P1) compared to sites with greater STP. Conversely, starter P improved early season growth even on high-P-testing soil in south-coastal British Columbia (Bittman et al. 2006), while large early season growth responses to starter fertilizer, regardless of STP levels were observed in Iowa (Bermudez and Mallarino 2002) and Minnesota (Kaiser et al. 2005). In our experiment, a site-year × fertilizer interaction showed that starter fertilizer increased ESB yield at Carman 2015 and Carman 2016, site-years with the highest (19 mg kg^{-1}) and second highest (9 mg kg^{-1}) STP concentrations, respectively. In contrast, ESB did not respond to starter fertilizer at Stephenfield 2015, the site-year with the lowest STP concentration (6 mg kg^{-1}). In our case, responsiveness was assessed in relation to the performance of the unfertilized control plots. Therefore, lack of response could be attributed to greater ESB measured in the unfertilized control at Stephenfield 2015, which may indicate that even with low STP concentration at this site, the juvenile crop was able to acquire the necessary nutrients for early season growth and development.

Greater overall ESB was recorded at Carman 2015, compared with equivalent fertilized treatments at the other two site-years (Table 2.5). However, the magnitude of ESB response to starter fertilizer relative to the control treatment was greater at Carman 2016 where, on average, starter fertilizer increased ESB yields by 149%, compared to Carman 2015, where the average increase was 55%. This variation in response may be attributed to the low ESB in the control treatment at Carman 2016, where the earlier planting date appeared to have restricted root development and early season plant growth, compared to the other two site-years.

Table 2.5 Early season biomass at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				kg ha^{-1}			
Canola	0	0	0	Control (no starter)	275	216	77	190*c*
	30	7.5	0	MAP + AS	482	265	305	351*ab*
	60	15	0	MAP + AS	543	253	344	380*a*
	30	7.5	0.75	MESZn	558	282	283	375*a*
	60	15	1.5	MESZn	561	273	369	401*a*
Soybean	0	0	0	Control (no starter)	425	279	176	293*b*
	30	7.5	0	MAP + AS	529	304	308	380*a*
	60	15	0	MAP + AS	577	318	375	423*a*
	30	7.5	0.75	MESZn	482	305	267	351*ab*
	60	15	1.5	MESZn	610	332	274	405*a*
Canola					484	258	276	339
Soybean					525	308	280	371
	0	0	0	Control (no starter)	350*Ac*	247*Ba*	127*Cc*	241
	30	7.5	0	MAP + AS	506*Ab*[c]	285*Ba*	306*Bab*	366
	60	15	0	MAP + AS	560*Aab*	286*Ca*	360*Ba*	402
	30	7.5	0.75	MESZn	520*Aab*	294*Ba*	275*Bb*	363
	60	15	1.5	MESZn	585*Aa*	302*Ba*	322*Bab*	403
Site-year					504	283	278	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.0383*
Crop*Fert	4	0.0025*
Site-year	2	<.0001*
Site-year*Fert	8	<.0001*
Site-year*Crop	2	0.3982
Site-year*Crop*Fert	8	0.1325
Coeff Var (C.V.)		39

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

2.4.3. Early Season Phosphorus Concentration in Plant Tissue (V4)

As expected, early season plant P concentrations at V4 increased with higher rates of fertilizer P (Table 2.6). On average, the low rates of P increased early season P concentrations by 30% relative to the control. Also, the high rates of starter fertilizer increased early season P concentrations by 20% relative to the low rates of starter fertilizer across both preceding crop treatments. These increases are similar to those observed in many other studies (Barry and Miller 1989; Jokela 1992; Lu and Miller 1993; Kaiser et al. 2005; Bittman et al. 2006; Roth et al. 2006).

The majority of research on tissue P critical concentration for corn has generally focused on analysis of mature leaves at early reproductive stages of development and research on tissue P sufficiency range in the vegetative stage is scarce, inconsistent and generally based on older research. Mallarino (1996) identified a critical concentration of 3.4 g P kg^{-1} for young corn plants at V5 to V6, and recent re-evaluation of critical P status for V5 to V6 corn in Iowa (Stammer 2015) identified a critical concentration range for P from 4.8 to 5.3 g P kg^{-1}. Schulte and Kelling (1991) identified tissue P sufficiency range between 0.40 and 0.60 % P (4 to 6 g P kg^{-1}) for whole corn plants sampled 24-45 days after planting. In the northern United States, AgVise Laboratories suggest tissue P sufficiency range between 3.6 and 8.0 g kg^{-1} for a corn crop that is 5 to 30 cm tall (Lee 2011); whereas in the southern parts of the United States, the North Carolina Department of Agriculture and Consumer Services Agronomic Division recently updated their reference tissue P sufficiency range to be between 3.0 and 5.0 g P kg^{-1} for a corn crop that is >10 cm in height to tasseling (Campbell and Plank 2013). Given this variability in literature values for the critical value of tissue P concentration for plants at V4, it is difficult to speculate whether or not all of the tissue P concentrations obtained in our fertilized treatments at the V4 stage were sufficient to obtain desired yields. However, the tissue P concentrations in the control plots were generally below these critical thresholds, especially for corn grown after canola.

All fertilized treatments significantly increased early season P concentration compared to the unfertilized control, and P concentration was similar for equivalent fertilized treatments, regardless of the preceding crop. However, there was a significant crop × fertilizer interaction. Relative to the unfertilized controls, the increase in early season P concentration with fertilized treatments was greater in corn after canola (60%) compared to corn after soybean (27%), because the unfertilized control in corn after canola had significantly lower early season P concentration, compared with the unfertilized control in corn after soybean. Further, prior to assessing P concentration in tissue at V4, P deficiency symptoms at V3 were more frequent and severe in the unfertilized control for corn after canola compared to corn after soybean (Appendix B.2). Application of Zn as MESZn in starter fertilizer did not have an effect on P concentration when compared with equivalent rates of MAP treatments, regardless of the preceding crop. This is contrary to findings by Cakmak and Marschner (1987), where low and high levels of Zn increased P concentrations in cotton grown under conditions of very low Zn by a factor of 10 and 5, respectively.

Table 2.6 Early season P concentration in plant tissue at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				g kg^{-1}			
Canola	0	0	0	Control (no starter)	2.9	3.1	2.0	2.7*d*
	30	7.5	0	MAP + AS	4.2	4.1	3.3	3.8*b*
	60	15	0	MAP + AS	5.5	4.8	4.0	4.8*a*
	30	7.5	0.75	MESZn	4.1	4.1	3.4	3.8*b*
	60	15	1.5	MESZn	5.3	4.5	4.1	4.6*a*
Soybean	0	0	0	Control (no starter)	3.6	3.6	2.9	3.3*c*
	30	7.5	0	MAP + AS	4.6	4.0	3.4	4.0*b*
	60	15	0	MAP + AS	5.2	4.4	4.2	4.6*a*
	30	7.5	0.75	MESZn	4.4	3.9	3.4	3.9*b*
	60	15	1.5	MESZn	5.2	4.6	3.9	4.6*a*
Canola					4.4	4.1	3.3	4.0
Soybean					4.6	4.1	3.5	4.1
	0	0	0	Control (no starter)	3.2*Ac*[c]	3.4*Ac*	2.4*Bc*	3.0
	30	7.5	0	MAP + AS	4.4*Ab*	4.0*Ab*	3.3*Bb*	3.9
	60	15	0	MAP + AS	5.4*Aa*	4.6*Ba*	4.1*Ba*	4.7
	30	7.5	0.75	MESZn	4.2*Ab*	4.0*Ab*	3.4*Bb*	3.9
	60	15	1.5	MESZn	5.3*Aa*	4.5*Ba*	4.0*Ca*	4.6
Site-year					4.5	4.1	3.4	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.2332
Crop*Fert	4	0.0003*
Site-year	2	0.0003*
Site-year*Fert	8	0.0133*
Site-year*Crop	2	0.4566
Site-year*Crop*Fert	8	0.5450
Coeff Var (C.V.)		21

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-d Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

A site-year × fertilizer interaction resulted in differences in P concentrations across sites varying with the fertilizer treatment. Carman 2016 had consistently lower early season P concentrations, compared to equivalent fertilized treatments at Carman 2015 (Table 2.6). The ranking of P concentrations at Stephenfield 2015 relative to the other two site-years varied with the rate and type of starter fertilizer. Lower early season P concentrations at Carman 2016 compared to Carman 2015 and Stephenfield 2015 could be attributed to the earlier planting date at Carman 2016, where P uptake was probably restricted due to cold soil conditions (Appendix I.8a).

2.4.4. Early Season Phosphorus Uptake (V4)

Corn P uptake was calculated from nutrient concentrations and oven-dried early season biomass (ESB) weights. Therefore, early season P uptake at V4 increased with greater ESB and higher rates of starter fertilizer (Table 2.7). However, analysis of variance indicated a significant crop × fertilizer interaction, similar to the interaction for ESB, where all fertilized treatments increased early season P uptake in corn after canola compared to the unfertilized control, while in corn after soybean, only three out of the four fertilized treatments (excluding the low rate of MESZn) significantly increased early season P uptake compared to the unfertilized control. Further, greater early season P uptake occurred in the unfertilized control for corn after soybean (1.0 kg ha^{-1}) compared with the unfertilized control for corn after canola (0.5 kg ha^{-1}). This difference could be attributed to greater ESB and greater early season P concentrations recorded for the unfertilized control in corn after soybean compared to the unfertilized control for corn after canola.

As previously discussed, P uptake may be more appropriate than colonization as a measure of AMF activity. Therefore, the greater early season P concentrations and early season P uptake reported in corn after soybean (mycorrhizal) unfertilized control compared to corn after canola (non-mycorrhizal) unfertilized control, may suggest that the AMF in corn plots following a mycorrhizal crop may have been more active (Biermann and Linderman 1981). However, this suggested explanation is not supported by the percent AMF colonization scores and their lack of response to preceding crop.

Table 2.7 Early season P uptake by corn at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				kg ha^{-1}			
Canola	0	0	0	Control (no starter)	0.8	0.7	0.2	0.5*e*
	30	7.5	0	MAP + AS	2.0	1.1	1.0	1.4*cd*
	60	15	0	MAP + AS	3.0	1.2	1.4	1.9*ab*
	30	7.5	0.75	MESZn	2.3	1.2	1.0	1.5*c*
	60	15	1.5	MESZn	3.0	1.2	1.5	1.9*ab*
Soybean	0	0	0	Control (no starter)	1.5	1.0	0.5	1.0*d*
	30	7.5	0	MAP + AS	2.4	1.2	1.0	1.5*bc*
	60	15	0	MAP + AS	3.0	1.4	1.6	2.0*a*
	30	7.5	0.75	MESZn	2.1	1.2	0.9	1.4*cd*
	60	15	1.5	MESZn	3.2	1.5	1.1	1.9*ab*
Canola					2.2	1.1	1.0	1.4
Soybean					2.4	1.3	1.0	1.6
	0	0	0	Control (no starter)	1.2*Ac*[c]	0.8*Ab*	0.3*Bc*	0.8
	30	7.5	0	MAP + AS	2.2*Ab*	1.1*Bab*	1.0*Bb*	1.5
	60	15	0	MAP + AS	3.0*Aa*	1.3*Ba*	1.5*Ba*	1.9
	30	7.5	0.75	MESZn	2.2*Ab*	1.2*Bab*	0.9*Bb*	1.4
	60	15	1.5	MESZn	3.1*Aa*	1.4*Ba*	1.3*Bab*	1.9
Site-year					2.3	1.2	1.0	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.0347*
Crop*Fert	4	0.0265*
Site-year	2	<.0001*
Site-year*Fert	8	<.0001*
Site-year*Crop	2	0.3623
Site-year*Crop*Fert	8	0.3154
Coeff Var (C.V.)		54

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-e Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

The site-year × fertilizer interaction was the result of the site differences varying with the fertilizer treatment and vice versa. For the fertilized treatments, Carman 2015 had the largest overall early season P uptake compared to Stephenfield 2015 and Carman 2016, which were similar to each other (Table 2.7). These differences in early season P uptake were due mainly to similar differences in ESB at these three site-years, where Carman 2015 had the greatest ESB at V4 compared to Stephenfield 2015 and Carman 2016. However, in the unfertilized control treatments, early season P uptake for Carman 2015 and Stephenfield 2015 were similar and substantially greater than for Carman 2016. Also, Stephenfield 2015 was the only site-year where the low rates of MAP and MESZn did not significantly increase early season P uptake in corn, relative to the unfertilized control. Only the high rates of MAP and MESZn increased early season P uptake at this site-year. One of the reasons for the modest differences in P uptake at this site-year is that ESB was similar for all fertilizer treatments, including the unfertilized control. Therefore, the differences in P uptake for this site-year were driven mainly by differences in P concentration, alone. Otherwise, Carman 2015 and Carman 2016 early season P uptake increased with all fertilized treatments, relative to the control and uptake was the greatest for treatments with the largest recorded ESB yields and highest rates of starter fertilizer.

2.4.5. Early Season Zinc Concentration in Plant Tissue (V4)

Early season Zn concentrations in corn plant tissue were greatest in the unfertilized control plots and MESZn treatment plots (Table 2.8). Both rates of MAP resulted in Zn concentrations that were lower than the unfertilized control. The P applied with the MAP treatments could have decreased Zn concentration in the corn plant (Elsokkary et al. 1981) by interfering with Zn translocation within the plant (Stukenholtz et al. 1966). Another explanation for this difference in early season Zn concentration could be nutrient dilution due to rapid ESB growth early on in the season. However, the application of Zn fertilizer with the MESZn treatments appeared to compensate to some degree for either or both mechanisms of lowering Zn concentrations, but only when applied at the high rate (1.5 kg Zn ha^{-1}). Nevertheless, neither rate of MESZn resulted in greater concentrations of Zn than in the unfertilized control treatment.

As anticipated, overall greatest early season Zn concentration in plant tissue was measured at Carman 2016 where the concentrations of DTPA-extractable Zn in soil were highest (1.91 mg kg^{-1}) followed by Carman 2015 (1.50 mg kg^{-1}) and Stephenfield 2015 (0.82 mg kg^{-1}).

2.4.6. Early Season Zinc Uptake (V4)

Analysis of variance showed a significant site-year × crop × fertilizer interaction (P=0.0457) for early season Zn uptake at V4, indicating that the crop × fertilizer interaction was not consistent across site-years (Table 2.9). Early season Zn uptake was not affected by starter fertilizer at Stephenfield 2015, a site-year where Zn concentrations were below the critical soil test threshold (1.0 mg kg^{-1}) for Zn fertilizer application to corn in Manitoba and also where ESB was unaffected by fertilizer treatment. At Carman 2015, three out of the four fertilizer treatments (excluding the low rate of MAP) increased Zn uptake in corn after canola and only the high rate of MESZn increased Zn uptake in corn after soybean, relative to the unfertilized controls. At Carman 2016, all fertilizer treatments increased early season Zn uptake in corn after canola and only the high rate of MAP increased Zn uptake in corn after soybean, relative to the unfertilized controls. Overall, compared to the unfertilized control treatments, both MAP and MESZn increased early season Zn uptake more consistently in corn after canola than in corn after soybean. Application of Zn fertilizer with the MESZn treatments did not consistently increase early season Zn uptake, compared to application of MAP and AS, alone.

Table 2.8 Early season Zn concentration in plant tissue at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				mg kg^{-1}			
Canola	0	0	0	Control (no starter)	36	20	39	32
	30	7.5	0	MAP + AS	28	19	34	27
	60	15	0	MAP + AS	32	17	32	27
	30	7.5	0.75	MESZn	33	20	36	30
	60	15	1.5	MESZn	34	21	40	31
Soybean	0	0	0	Control (no starter)	31	23	40	31
	30	7.5	0	MAP + AS	32	19	38	30
	60	15	0	MAP + AS	28	19	33	27
	30	7.5	0.75	MESZn	34	21	35	30
	60	15	1.5	MESZn	35	23	37	32
Canola					33	19	36	29
Soybean					32	21	36	30
	0	0	0	Control (no starter)	34	22	39	32*a*[c]
	30	7.5	0	MAP + AS	30	19	36	28*bc*
	60	15	0	MAP + AS	30	18	32	27*c*
	30	7.5	0.75	MESZn	33	20	36	30*ab*
	60	15	1.5	MESZn	35	22	38	31*a*
Site-year					32B[c]	20C	36A	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.5513
Crop*Fert	4	0.2977
Site-year	2	<.0001*
Site-year*Fert	8	0.6406
Site-year*Crop	2	0.4873
Site-year*Crop*Fert	8	0.0557
Coeff Var (C.V.)		27

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping; A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Table 2.9 Early season Zn uptake by corn at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				kg ha^{-1} ×10^{-2}			
Canola	0	0	0	Control (no starter)	1.0*Ae* [c]	0.5*Ba*	0.3*Bc*	0.6
	30	7.5	0	MAP + AS	1.4*Acde*	0.5*Ba*	1.0*Aab*	1.0
	60	15	0	MAP + AS	1.7*Aabcd*	0.4*Ca*	1.1*Bab*	1.1
	30	7.5	0.75	MESZn	1.9*Aabc*	0.6*Ca*	1.0*Bab*	1.1
	60	15	1.5	MESZn	1.9*Aab*	0.6*Ca*	1.5*Ba*	1.3
Soybean	0	0	0	Control (no starter)	1.3*Ade*	0.7*Ba*	0.7*Bbc*	0.9
	30	7.5	0	MAP + AS	1.7*Aabcd*	0.6*Ca*	1.1*Bab*	1.1
	60	15	0	MAP + AS	1.6*Abcd*	0.6*Ba*	1.2*Aa*	1.1
	30	7.5	0.75	MESZn	1.6*Abcd*	0.7*Ba*	1.0*Bab*	1.1
	60	15	1.5	MESZn	2.1*Aa*	0.8*Ba*	1.0*Bab*	1.3
Canola					1.6	0.5	1.0	1.0
Soybean					1.7	0.7	1.0	1.1
	0	0	0	Control (no starter)	1.2	0.6	0.5	0.7
	30	7.5	0	MAP + AS	1.5	0.6	1.1	1.1
	60	15	0	MAP + AS	1.7	0.5	1.2	1.1
	30	7.5	0.75	MESZn	1.7	0.6	1.0	1.1
	60	15	1.5	MESZn	2.0	0.7	1.2	1.3
Site-year					1.6	0.6	1.0	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.0491*
Crop*Fert	4	0.0228*
Site-year	2	<.0001*
Site-year*Fert	8	<.0001*
Site-year*Crop	2	0.5736
Site-year*Crop*Fert	8	0.0457*
Coeff Var (C.V.)		51

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-e Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Relating Zn uptake to Zn concentration, it should be noted that early season uptake of Zn in several of the MAP treatments was much greater than in the control treatments, in spite of the lower concentrations of Zn in plant tissue reported earlier. This is known as the Steenberg effect, where the addition of nutrients causes plant biomass to increase more rapidly than nutrient concentrations (Havlin et al. 2004). In our study, MAP increased early season biomass by an average of 58%, regardless of the preceding crop, and lowered Zn concentrations by only 14% compared to the control, resulting in a substantial increase in Zn uptake, in spite of lower concentrations of Zn.

2.4.7. Plant Height (V7)

In our experiment, all starter fertilizer treatments increased plant height at V7 at all site-years, compared to the unfertilized control (Table 2.10). Similar overall responses of early season plant height to starter fertilizer were reported by Mascagni and Boquet (1996), Bundy and Andraski (1999), Cromley et al. (2006) and Kaiser et al. (2016). Further, Kaiser et al. (2016) concluded that greater early season plant height was also associated with accelerated maturity and silking, while Bundy and Andraski (1999) indicated that a profitable yield response is not always guaranteed with a positive height response to starter fertilizer. However, starter fertilizer increased plant height at V7 by 28 cm for corn after canola and only 16 cm for corn after soybean, compared to their respective unfertilized controls, resulting in a crop x fertilizer interaction. However, similar to what we observed early in the growing season for ESB response to starter fertilizer, there were no differences in plant height among the fertilized treatments. The control for corn after soybean had significantly taller plants (126 cm) compared to the control for corn after canola (109 cm).

A site-year × fertilizer interaction showed that the magnitude of early season plant height response to starter fertilizer, relative to the unfertilized control was greater at Carman 2016 (31%) compared to Carman 2015 (19%) and Stephenfield 2015 (11%). The difference in plant height response to starter fertilizer between site-years could be due to earlier planting date at

Carman 2016, where root development and early season plant growth appeared to have been impeded by cold soil temperatures (Appendix I.8a).

Table 2.10 Early season plant height at V7: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				cm			
Canola	0	0	0	Control (no starter)	116	123	87	109*c*
	30	7.5	0	MAP + AS	147	141	123	137*a*
	60	15	0	MAP + AS	144	143	128	138*a*
	30	7.5	0.75	MESZn	148	140	119	136*a*
	60	15	1.5	MESZn	145	141	128	138*a*
Soybean	0	0	0	Control (no starter)	131	141	106	126*b*
	30	7.5	0	MAP + AS	146	151	126	141*a*
	60	15	0	MAP + AS	148	151	133	144*a*
	30	7.5	0.75	MESZn	145	149	124	139*a*
	60	15	1.5	MESZn	152	149	132	144*a*
Canola					140	138	117	131
Soybean					144	148	124	139
	0	0	0	Control (no starter)	124*Ab*[c]	132*Ab*	97*Bc*	117
	30	7.5	0	MAP + AS	147*Aa*	146*Aa*	124*Bab*	139
	60	15	0	MAP + AS	146*Aa*	147*Aa*	131*Ba*	141
	30	7.5	0.75	MESZn	146*Aa*	145*Aa*	121*Bb*	138
	60	15	1.5	MESZn	148*Aa*	145*Aa*	130*Ba*	141
Site-year					142	143	121	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.0058*
Crop*Fert	4	<.0001*
Site-year	2	<.0001*
Site-year*Fert	8	<.0001*
Site-year*Crop	2	0.5766
Site-year*Crop*Fert	8	0.7092
Coeff Var (C.V.)		12

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

2.4.8. Days from Planting to Silking (R1)

Analysis of variance indicated a significant site-year × crop × fertilizer interaction for days from planting to silking, indicating that the crop × fertilizer interaction was not consistent across site-years (Table 2.11, Appendix C.1b).

Starter fertilizer reduced days to silking at Carman 2015 and Carman 2016 relative to the unfertilized controls. The three-way interaction indicated that at Carman 2015 application of starter fertilizer reduced days to silking by 2 d relative to the unfertilized control in corn after canola, but not in corn after soybean. Further, at Carman 2016 application of starter fertilizer reduced days to silking by 7 and 2 d in corn after canola and corn after soybean, respectively, relative to their respective unfertilized controls. The unfertilized control for corn after soybean reached the silking stage 2 and 5-d prior to the unfertilized control for corn after canola at Carman 2015 and Carman 2016, respectively and all fertilized plots reached silking on the same day at each site-year, regardless of the preceding crop. In contrast, maturity responses to starter fertilizer were not observed at Stephenfield 2015, where the unfertilized control treatments reached silking on the same day as fertilized plots, regardless of the preceding crop.

Similar to our findings, Bullock et al. (1993) reported that tassel and black-layer appeared 2-3 d earlier with in-furrow liquid starter fertilizer, compared with unfertilized control treatments. Mascagni and Boquet (1996) also reported 3-5 d reduction in days to silking with starter fertilizer. Conversely, other studies showed that starter fertilizer had no effect on the number of days to reach physiological maturity (R6) (Cromley et al. 2006) or the number of days in the grain fill period (Gordon et al. 1997).

With respect to some of the main effects, days from planting to silking were delayed by 12 d at Carman 2016 compared to Carman 2015 and Stephenfield 2015, regardless of the preceding crop or fertilized treatment. This difference in days to silking was probably due to earlier planting date (2 wk) at Carman 2016, where cool temperatures in the early part of the growing season extended the time for reaching all stages of phenological development. Starter fertilizer decreased time to silking at Carman 2015 and Carman 2016, where at both of these site-years large increases in early season plant heights and ESB compared to the unfertilized control occurred. Similarly, Kaiser et al. (2016) observed that greater early season plant height was associated with shorter time from planting to silking, regardless of planting date or hybrid maturity.

Table 2.11 Days from planting to silking: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				DAP[c]			
Canola	0	0	0	Control (no starter)	65.0*Ba*[d]	63.0*Ca*	79.5*Aa*	68.8
	30	7.5	0	MAP + AS	62.2*Bb*	62.0*Ba*	73.0*Ac*	65.6
	60	15	0	MAP + AS	63.5*Bb*	61.8*Ca*	72.2*Ac*	65.7
	30	7.5	0.75	MESZn	63.0*Bb*	61.3*Ca*	72.2*Ac*	65.3
	60	15	1.5	MESZn	62.5*Bb*	61.8*Ca*	72.5*Ac*	65.4
Soybean	0	0	0	Control (no starter)	62.7*Bb*	62.5*Ba*	74.7*Ab*	66.4
	30	7.5	0	MAP + AS	62.0*Bb*	61.5*Ba*	72.5*Ac*	65.1
	60	15	0	MAP + AS	62.0*Bb*	61.8*Ba*	72.7*Ac*	65.3
	30	7.5	0.75	MESZn	62.0*Bb*	61.8*Ba*	72.5*Ac*	65.2
	60	15	1.5	MESZn	62.0*Bb*	62.0*Ca*	72.5*Ac*	65.3
Canola					63.2	61.9	73.8	66.1
Soybean					62.1	61.9	73.0	65.5
	0	0	0	Control (no starter)	63.9	62.7	77.1	67.6
	30	7.5	0	MAP + AS	62.1	61.7	72.7	65.3
	60	15	0	MAP + AS	62.7	61.8	72.5	65.5
	30	7.5	0.75	MESZn	62.5	61.5	72.4	65.3
	60	15	1.5	MESZn	62.3	61.9	72.5	65.4
Site-year					62.7	61.9	73.4	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.0003*
Crop*Fert	4	<.0001*
Site-year	2	<.0001*
Site-year*Fert	8	<.0001*
Site-year*Crop	2	0.0217*
Site-year*Crop*Fert	8	0.0015*
Coeff Var (C.V.)		8

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] DAP, days after planting.
[d] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

2.4.9. Late Season Cob Moisture (R4 - Harvest)

Late season cob moisture data was not combined across site-years and each site-year was analyzed separately because sampling dates and frequency of sampling varied between site-years.

Starter fertilizer decreased late season cob moisture only at Stephenfield 2015 (P= 0.0064, Fig. 2.1, Appendix C.2b), while cob moisture was not influenced by starter fertilizer at the other two site-years ($P>0.05$, Fig. 2.1, Appendix C.2a-c). A fertilizer × date interaction showed that cob moisture declined with the application of side banded fertilizer on four of five sampling dates at Stephenfield 2015. On the second sampling date (2015 Sep. 12), the high rate of MAP and MESZn significantly reduced cob moisture by 3-5 g kg^{-1}. However, at the next sampling date (2015 Sep. 21), only the low rate of MESZn significantly reduced cob moisture relative to the control, although all starter fertilizer treatments had similar cob moisture. On the last two dates of sampling (2015 Sep. 28 and Oct. 05), only the high rate of MESZn reduced cob moisture, by 3-4 g kg^{-1}, relative to the unfertilized control. However, on these last two sampling dates the moisture content for the high rate of MESZn was not statistically different from the high rate of MAP or any of the other starter fertilizer treatments, respectively.

Considering the lack of early and mid season response to starter fertilizer at Stephenfield, the accelerated corn cob drydown in response to starter fertilizer is unusual. A starter effect this late in the season, given the absence of early season biomass and maturity responses to starter fertilizer is difficult to explain. However, all things considered, an accelerated dry-down could lead to a more timely harvest, especially when racing against the threat of fall frost and poor harvesting conditions (Nielsen 2013).

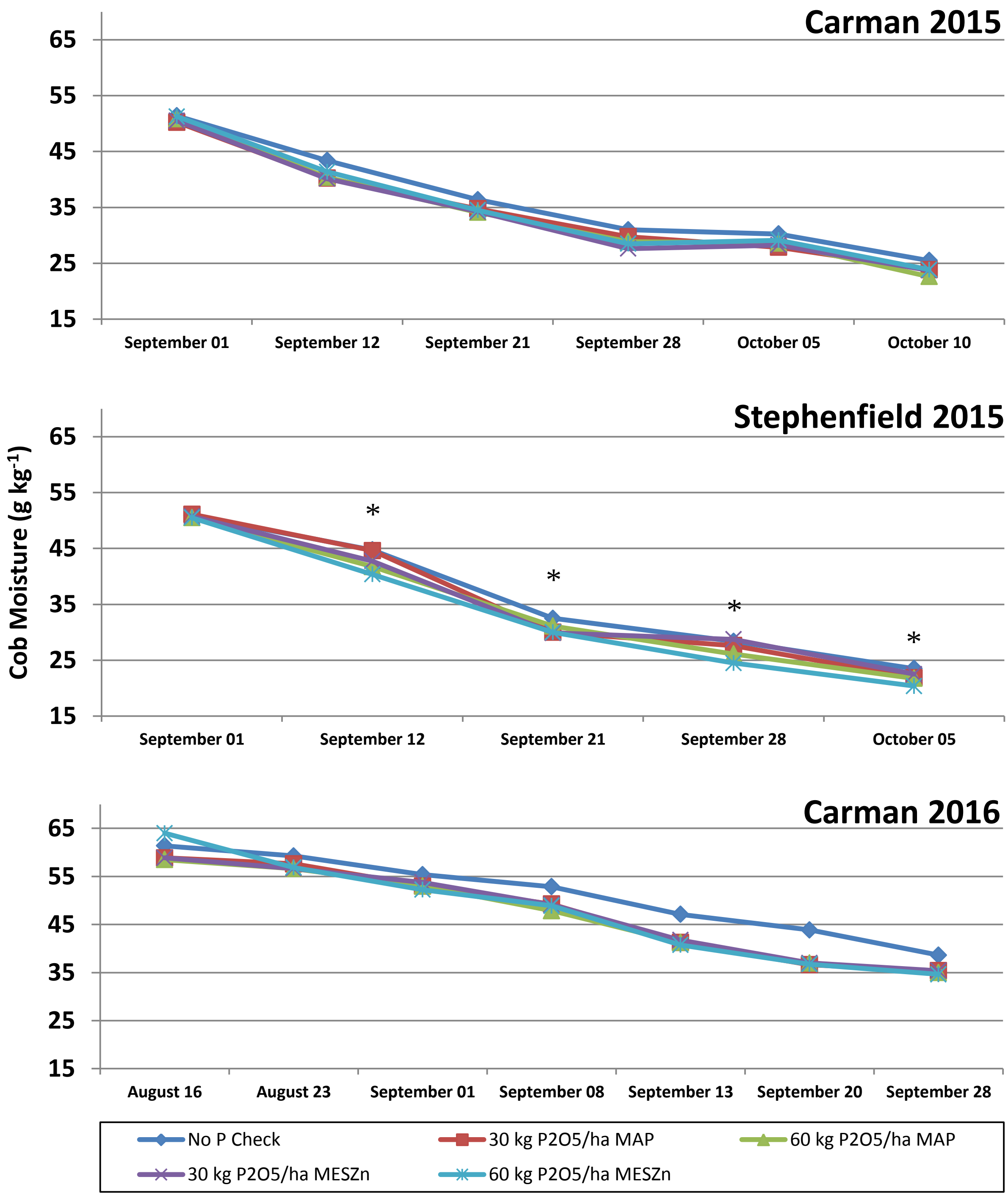


Figure 2.1. Late season cob moisture as affected by starter fertilizer applied in a 5 cm × 2.5 cm spring side band, measured from R4 until harvest (fertilizer × date) at Carman 2015, Stephenfield 2015 and Carman 2016. Asterisks (*) indicate significant differences between fertilizer treatments (P<0.05).

2.4.10. Grain Moisture at Harvest

Analysis of variance indicated a significant crop × fertilizer interaction for grain moisture at harvest. In corn after canola, the average grain moisture was 2.4 g kg^{-1} greater in the unfertilized control than in the starter fertilizer treatments (Table 2.12), while the corn after soybean unfertilized control was not statistically different from any of the starter fertilizer treatments. However, all starter fertilizer treatments had the same moisture at harvest, regardless of the preceding crop, and so the grain moisture response to starter fertilizer for each preceding crop was largely influenced by the unfertilized controls. Mascagni and Boquet (1996) and Kaiser et al. (2016) reported 7 to 14 and 2 g kg^{-1} reduction in grain moisture at harvest with the application of in-furrow starter fertilizer, respectively. However, there were no grain moisture differences reported by Bullock et al. (1993) with in-furrow fertilizer, relative to unfertilized treatments. Conversely, Bundy and Andraski (1999) observed a reduction in corn grain moisture content only at sites with more rapid crop development as part of the starter effect. Thus, considering that in our experiment the greatest reduction in days to silking with starter fertilizer was observed in corn after canola compared to the unfertilized control, accelerated maturity may have contributed to the reduction of grain moisture at harvest in corn planted with starter fertilizer relative to its respective unfertilized control, only after canola, .

Nevertheless, even a small reduction in grain moisture at harvest, such as the one observed in our experiment can help reduce drying costs and as a result, potentially cover the cost of starter fertilizer, even when application of starter fertilizer does not influence net return with an increase in grain yield (Kaiser et al. 2016). Reduced grain moisture decreases the need for artificial drying after harvest, speeds up the harvest progress and decreases the need for larger dryer capacity (Nielsen 2013).

Table 2.12 Grain moisture at harvest: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				g kg^{-1}			
Canola	0	0	0	Control (no starter)	21.2	18.8	28.2	22.7*a*
	30	7.5	0	MAP + AS	19.8	17.0	24.7	20.5*bc*
	60	15	0	MAP + AS	19.9	16.7	24.2	20.2*c*
	30	7.5	0.75	MESZn	19.4	17.2	25.3	20.6*bc*
	60	15	1.5	MESZn	19.9	15.9	24.2	20.0*c*
Soybean	0	0	0	Control (no starter)	20.7	18.3	26.0	21.6*ab*
	30	7.5	0	MAP + AS	20.1	17.9	24.6	20.9*bc*
	60	15	0	MAP + AS	20.6	17.2	24.2	20.7*bc*
	30	7.5	0.75	MESZn	20.2	18.1	25.0	21.1*bc*
	60	15	1.5	MESZn	20.7	17.1	24.0	20.6*bc*
Canola					20.0	17.1	25.3	20.8
Soybean					20.5	17.7	24.7	21.0
	0	0	0	Control (no starter)	20.9Ba[c]	18.5Ca	27.1Aa	22.2
	30	7.5	0	MAP + AS	19.9Bb	17.5Cbc	24.7Abc	20.7
	60	15	0	MAP + AS	20.2Bab	16.9Cbc	24.2Abc	20.5
	30	7.5	0.75	MESZn	19.8Bb	17.6Cab	25.1Ab	20.9
	60	15	1.5	MESZn	20.3Bab	16.5Cc	24.1Ac	20.3
Site-year					20.2	17.4	25.0	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.5579
Crop*Fert	4	0.0002*
Site-year	2	<.0001*
Site-year*Fert	8	0.0001*
Site-year*Crop	2	0.1584
Site-year*Crop*Fert	8	0.9252
Coeff Var (C.V.)		16

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Stephenfield 2015 had the lowest grain moisture at harvest, followed by Carman 2015 and Carman 2016 for equivalent treatments (Table 2.12). However, the site-year × fertilizer interaction showed significant differences in grain moisture response to starter fertilizer among site-years. All starter fertilizer treatments reduced grain moisture by an average of 2.6 g kg^{-1} at Carman 2016 relative to the unfertilized control, whereas only three out of the four fertilized treatments (excluding low rate of MESZn) reduced moisture, by an average of 1.5 g kg^{-1}, at Stephenfield 2015. At Carman 2015 only the low rates of MAP and MESZn significantly reduced grain moisture, by an average of 1.0 g kg^{-1}, compared to the unfertilized control.

Average growing season air temperature was cooler at Carman 2016 than for other site-years and this site-year also received more total precipitation compared to the other two site-years. Under such cool and moist conditions, Kaiser et al. (2015) reported that application of starter fertilizer can decrease grain moisture by as much as 2 g kg^{-1}. Additionally, the greater grain moisture response to starter fertilizer at Carman 2016, compared to the other two site-years could also be due to the timing of harvest, because the starter effect is more likely to occur when fields are harvested early and grain moisture is in the range of 20-30 g kg^{-1} (Kaiser et al. 2015).

2.4.11. Grain Yield (Harvest)

Grain yield was influenced by a site-year × crop interaction (Table 2.13). Corn after soybean out-yielded corn after canola at Stephenfield 2015 by 659 kg ha^{-1}; however, for the other two site-years, the yields for corn after canola were similar to those for corn after soybean.

Although there were no significant grain yield differences among any of the starter fertilizer treatments, only the high rate of MAP significantly increased grain yields by 770 kg ha^{-1} compared to the unfertilized control, regardless of the preceding crop. Grain yield increases in response to starter fertilizer have been reported in previous studies (Bundy and Andraski 1999; Bermudez and Mallarino 2002; Niehues et al. 2004).

In contrast to our findings, many studies report negligible or lack of grain yield responses to starter fertilizer, even in cases where starter fertilizer application substantially and frequently increased early season plant growth (Bullock et al. 1993; Kaiser et al. 2005, 2015, 2016; Roth et al. 2006; Wortmann et al. 2006; Rehm and Lamb 2009; Kim et al. 2013). In our experiment, although early season biomass and plant height responses were much larger (on a percent basis) than grain yield responses, placement of the high rate of MAP near the seed and greater early season P uptake still had a positive effect on grain yield response at the end of the season.

Table 2.13 Grain yield at harvest: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				kg ha^{-1} (adjusted to 155 g kg^{-1} moisture)			
Canola	0	0	0	Control (no starter)	10057	6693	10983	9244
	30	7.5	0	MAP + AS	9611	7488	12418	9839
	60	15	0	MAP + AS	10717	7428	12647	10264
	30	7.5	0.75	MESZn	10234	7858	11956	10016
	60	15	1.5	MESZn	10044	7641	12331	10005
Soybean	0	0	0	Control (no starter)	10213	7418	12225	9952
	30	7.5	0	MAP + AS	10117	8082	12215	10138
	60	15	0	MAP + AS	10178	8791	12445	10471
	30	7.5	0.75	MESZn	9520	8243	12147	9970
	60	15	1.5	MESZn	9826	7865	12292	9994
Canola					10133*Ba*[c]	7421*Cb*	12067*Aa*	9874
Soybean					9971*Ba*	8080*Ca*	12265*Aa*	10105
	0	0	0	Control (no starter)	10135	7056	11604	9598*b*
	30	7.5	0	MAP + AS	9864	7785	12316	9988*ab*
	60	15	0	MAP + AS	10448	8109	12546	10368*a*
	30	7.5	0.75	MESZn	9877	8050	12051	9993*ab*
	60	15	1.5	MESZn	9935	7753	12311	10000*ab*
Site-year					10052	7751	12166	
ANOVA				Df	Pr>F			
Fert				4				0.0017*
Crop				1				0.0415*
Crop*Fert				4				0.2176
Site-year				2				<.0001*
Site-year*Fert				8				0.1587
Site-year*Crop				2				0.0139*
Site-year*Crop*Fert				8				0.2003
Coeff Var (C.V.)								19

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

2.5. Conclusions

Contrary to our hypothesis, previous cropping of canola did not restrict arbuscular mycorrhizal fungi colonization of corn relative to that observed in corn after soybean. Considering the high overall levels of colonization reported at V4, perhaps our measurements were too late to observe differences in AMF colonization that may have occurred earlier in the growing season. Corn after canola in the unfertilized control treatment had consistently lower early season biomass, lower plant tissue P concentrations and lower P and Zn uptake, compared to corn after soybean. Therefore, although the quantity of AMF in corn roots following the two preceding crops was not significantly different, the activity levels may have differed, and corn after canola was unable to acquire the same amount of nutrients as corn after soybean.

Starter fertilizer increased early season growth, plant height, P concentration, and uptake of P and Zn in plant tissue, relative to the unfertilized control. The early season plant growth response and greater nutrient uptake with starter fertilizer further accelerated silking by 2-7 d and reduced grain moisture at harvest by 2-3 g kg^{-1}. The combined effect of positive early and mid season responses appear to have helped the crop realize more of its yield potential by the end of the growing season, and the grain yield increased by 770 kg ha^{-1} with the application of the high rate of MAP.

Overall, placement of starter fertilizer in close proximity to the seed provided adequate nutrition to the corn crop and the response to starter fertilizer was similar, regardless of the preceding crop. Therefore, the negative influence of preceding canola crop on early season growth and mid season development of corn can be managed with starter fertilization, to provide adequate P and Zn to the corn crop and maintain successful production.

3. CORN RESPONSE TO PHOSPHORUS IN CONVENTIONAL VERSUS STRIP-TILL AS A MEANS FOR TESTING ALTERNATIVE CROP RESIDUE MANAGEMENT PRACTICES FOR CORN PRODUCTION IN MANITOBA

Keywords: *Zea mays* L., phosphorus, strip-till, early season biomass, plant height, maturity, grain moisture, grain yield

3.1. Abstract

Strip-till is an emerging residue management system, well suited to corn production and as grain corn *(Zea mays* L) acreage in Manitoba increases, adoption of strip-tillage may become more common. A residue management study conducted for two corn test crop years evaluated corn response to phosphorus rate, placement and timing in strip-tillage and conventional tillage. Treatments included a control (no P), two rates of P (30 and 60 kg P_2O_5 ha^{-1}) in the form of monoammonium phosphate (MAP, 11-52-0), applied either in the fall as a deep band (10-13 cm deep) under the intended seedrow with a strip-till unit or in the spring as a side band 5 cm beside and 2.5 cm below the seed, with a corn planter. At Carman, spring side banded P treatments increased early season biomass by up to 103% compared to the unfertilized controls. Banded P treatments reduced days to silking by 2-3 d at Carman, compared to the unfertilized controls. Spring side banded P treatments increased grain yield by an average of 467 kg ha^{-1} relative to the unfertilized control. Overall, side banded P at planting was agronomicially superior to precision fall banding for corn. Also, there was no agronomic penalty for corn grown with strip-tillage, compared to conventional tillage.

3.2. Introduction

Conservation tillage, such as the no-till system is a residue management practice that helps conserve soil and water, minimize short term drought, maintain and improve soil structure and potentially reduce production costs (Singh et al. 1966; Arshad and Azooz 1996; Bermudez and Mallarino 2002; Boomsma et al. 2006). However, farmers may initially be reluctant to adopt conservation tillage practices due to possible negative experiences and perceptions associated with no-till systems when compared to conventional tillage systems, especially in the cold, northern crop production areas, where the growing season is relatively short. Some of the perceived drawbacks include, lower early season soil temperatures, poor germination and stand establishment, delayed phenological development, and the potential for reduced grain yields (Swan et al. 1994; Bermudez and Mallarino 2004; Niehues et al. 2004; Boomsma et al. 2006).

With these considerations in mind, strip-till is an emerging residue management system that incorporates the soil and water conservation benefits of no-till systems and the improved seedbed conditions of conventional tillage systems. With corn (*Zea mays* L) production having increased by 30% in 2016 (Statistics Canada 2016), Manitoba corn growers may benefit from a refined conservation tillage practice that is not only environmentally but also economically sound. Strip-tillage operations create narrow, residue-free strips of soil that are about 20 cm wide on 0.76-m centres. The soil surface between these strips is left undisturbed, similar to no-till, and accounts for more than the 20% of residue cover required for significant reductions in soil erosion (Vyn and Raimbault 1992). Optimum timing of the strip-till operation varies with region. However, especially in areas such as Manitoba where the growing season is short, fall strip-tillage is often preferred because it allows for the fastest soil warm-up in the spring and most reliable seed-to-soil contact (Nowatzki et al. 2011).

Nevertheless, even with a modified conservation tillage system such as strip-till, the crop residue left on the surface will continue to act as an insulating layer over the soil surface (Niehues et al. 2004), and may result in cooler soil conditions at the time of planting and early stages of growth (Gordon and Whitney 1995). These conditions may reduce the rate of root growth and plant P uptake, aggravating P deficiency (Osborne 2005), compared to conventional tillage systems. Therefore, under conservation tillage, application of starter P fertilizer can improve early season crop development and P nutrition (Bundy and Andraski 1999; Bermudez and Mallarino 2002; Kaiser et al. 2005; Roth et al. 2006; Wortmann et al. 2006; Kim et al. 2013), potentially reduce moisture at harvest (Mascagni and Boquet 1996) and, to a lesser extent, increase yield (Bundy and Andraski 1999).

Starter fertilizers are small amounts of fertilizer placed in close proximity to the seed to meet the demands of the seedling early in the season, until the plant's root system develops (Beegle et al. 2007). Generally, nutrients that are included in starter fertilizer are P and nitrogen (N); however, in some cases micronutrients may be added (Beegle et al. 2007; Hergert et al. 2012). Many different fertilizer sources can be used, including ammonium nitrate (34-0-0) and ammonium sulphate (21-0-0-24S) for N or N-S starters, triple super phosphate (0-45-0) for P-only starter, and ammonium polyphosphate (10-34-0) or monoammonium phosphate (11-52-0) for N-P starter. However, starter fertilizer response is generally attributed mostly to the inclusion of P in the mixture due to the plant's large early season requirements for this essential nutrient (Randall and Hoeft 1988).

Osborne (2005) evaluated corn yield response to starter fertilizer in conventional tillage and fall strip-tillage and found that corn yield increased, even on soils with high levels of P fertility, regardless of the type of residue management. Alternatively, research in Indiana showed that corn response to starter fertilizer was more frequent in no-till than in conventional tillage production systems (Scharf 1999). Other studies have found also that response to starter fertilizers was greatest under environmental conditions where cool soils limit early plant development and where P fertility was below optimum levels for corn (Gordon et al. 1997; Bermudez and Mallarino 2002; Mallarino et al. 2011).

Overall, the goal of starter fertilizer is economic profitability and beneficial response to these treatments in production systems (Bundy and Andraski 1999). Current recommended placement of starter fertilizer for corn is 2” beside and 2” below the seed band (Bittman et al. 2000) because it allows more flexibility than in-row placement with respect to the rates of fertilizer that can be safely applied in close proximity to the seed (Niehues et al. 2004). Banding P is a more agronomically efficient and environmentally sustainable placement, compared to broadcast applications (Heard et al. 2014). Placement near the seed provides excellent access to nutrients for root uptake, especially soon after germination when cool soil conditions often limit nutrient availability and root development (Jokela 1992). Deep banding of fertilizer has also been shown to outperform broadcast applications, especially under conditions of conservation tillage (Randall and Hoeft 1988). However, in other studies, strip-till corn has not yielded consistently more when P was deep banded compared to broadcast placement (Borges and Mallarino 2001; Vyn 2008). Most strip-till units allow for simultaneous deep banding of fertilizers during the tillage operation, which helps build soil-test P levels and potentially increase fertilizer use efficiency compared to broadcast applications (Borges and Mallarino 2001; Vyn 2008). However, compared to a spring side band starter fertilizer application, a fall deep band could allow more time for P retention reactions by soil (Wolkowski 2000). On the other hand, growers also need to consider that the logistics of using spring applied starter fertilizer may slow down their planting operation by roughly 10-15% (Scharf 1999). Therefore, optimizing placement of starter P is attracting more interest from growers as tillage systems are refined, economic profitability becomes tighter and equipment manufacturers attempt to improve equipment and develop attachments to balance productivity with conservation goals (Randall and Hoeft 1988; Wolkowski 2000).

Another consideration for growers when adopting a tillage practice, is the role of arbuscular mycorrhizal fungi (AMF) in corn nutrition and the effect of soil disturbance on AMF quantity and colonization (Landry et al. 2008). Arbuscular mycorrhizal fungi are widely distributed in natural and agricultural soils. Mycorrhizal association can enhance plant uptake of P via extensive hyphal networks in soil, while the fungi benefit by having access to plant-assimilated carbon (Miller 2000; An et al. 2010; Monreal et al. 2011). Strip-till has a minimal effect on soil disturbance, while conventional tillage operations impose high levels of soil disturbance, effectively breaking-up roots and extraradical mycelium (Landry et al. 2008). Disturbance of the hyphal network, which is an important component of colonization, affects early season corn nutrition because the corn roots are unable to quickly attach to the AMF system and P absorption is reduced (Evans and Miller 1990; McGonigle and Miller 1993; Galvez et al. 2001). However, if AMF colonization is impeded by practices such as conventional tillage, application of starter fertilizers may improve production and nutrient uptake early in the growing season (Bittman et al. 2006; Kaiser et al. 2015).

With various fertilizer placement methods being used, hybrid selection is also an important factor to consider in a corn production system. Differences in morphological and physiological root characteristics may influence the uptake of soil nutrients by individual corn genotypes and influence the effectiveness of starter fertilizer (Mengel and Barber 1974; Gordon et al. 1997; Gordon and Pierzynski 2006). A study in Florida (Teare and Wright 1990) reported that only 8 out of 21 tested corn hybrids consistently had a positive response to starter fertilizer, compared to several other hybrids that responded negatively to the same application. However, studies out of Iowa (Buah et al. 1999) and Missouri (Cromley et al. 2006) showed no differences in response to starter fertilizer for all hybrids tested. Consequently, economic implications need to be considered since beneficial response to starter fertilizer may vary among different hybrids (Bundy and Andraski 1999).

Therefore, with all the above considerations in mind, including increasing corn acreage and the ongoing conservation tillage efforts in Manitoba, an experiment was set-up to evaluate corn response to phosphorus rate, placement and timing in strip-tillage and conventional tillage. We hypothesized that addition of starter P would improve early corn development and increase yields and that side banding P in the spring in close proximity to the seed would outperform fall deep-banded P applications. Furthermore, the agronomic benefits of starter P would be greater in strip-till than conventional till due to slower diffusion of P in the strip-till system.

3.3. Materials and Methods

3.3.1 Site Descriptions and Characteristics

Preference was given to field sites with low to medium Olsen extractable soil test P ($\leq$15 mg kg^{-1}) and good drainage. To determine site suitability for the residue management study, 12 - 20 soil cores were collected in the fall of 2014 and 2015 from potential sites. Soil cores were divided into 0-15 and 15-60 cm depths and matching depths were combined into a composite sample. Each sample was sent to AgVise Laboratories (Northwood, ND, USA) for complete soil analysis (0-15 cm depth: phosphorus, potassium, zinc, organic matter, calcium, magnesium, sodium, CEC, base saturation, iron, manganese, copper, boron; 15-60 cm depth: nitrogen, pH, salts, sulphur, carbonates, chloride). Soil test P concentration was determined by sodium bicarbonate (Olsen), zinc by DTPA, pH and salts determined in 1:1 soil:water ratio, nitrate concentration by cadmium reduction, carbonates by pressure method, organic matter by loss on ignition, exchangeable potassium by ammonium acetate and sulphur (sulphate) by the turbidometric method.

The four selected sites included, Carman, MB (University of Manitoba's Ian N. Morrison Research Farm) (49°29' N, 98° 2' W, 2015) and (49°29' N, 98° 2' W, 2016) , Portage la Prairie, MB (Canada-Manitoba Crop Diversification Centre) (49°57' N, 98°16' W, 2015) and (49°57' N 98°16' W, 2016).

At each site-year, there was uniform cereal grain production prior to planting corn as a test crop in 2015 and 2016. Following cereal harvest, 10 soil cores were collected from each site in the fall at two depths (0-15 and 15-60 cm) to determine basal rates of any additional nutrients such as potassium (K), sulphur (S) or micronutrients and to measure nitrate-N to determine N fertilizer requirements. If K was needed, it was applied as a deep band in the fall and, if the entire recommended rate of K could not be applied in the fall, additional K was side banded with the corn planter in the spring.

Additional rates of soil-applied S were applied in the spring, at planting or early in the growing season, according to fall soil test recommendations. Due to fall fertilizer applications for some treatments, there was no soil sampling in the spring.

Soil texture was determined using the pipette method to determine particle size (Carter and Gregorich 2008) and classified according to the Canadian System of Soil Classification (Soil

Classification Working Group 1998). Soil phosphorus concentrations ranged from 5 to 14 mg kg^{-1} Olsen extractable P.

Table 3.1 Soil characteristics at each site-year, in fall prior to tillage

Site-Year	Soil Series[a]	Texture[b]	Particle Distribution			Soil Test[c]	
			Sand	Silt	Clay	P	pH
			g kg^{-1}			mg kg^{-1}	
Carman 2015	Hochfeld	LFS	820	70	110	8 (L)[d]	6.0
Portage la Prairie 2015	La Salle	CL	270	470	260	11 (M)	8.0
Carman 2016	Rignold	C	360	240	400	5 (L)	5.1
Portage la Prairie 2016	Dugas	SiL	170	590	250	14 (M)	7.5

[a] Soil series information obtained from Detailed Soil Survey Maps and Reports (https://www.gov.mb.ca/agriculture/land/soil-survey/importance-of-soil-survey-mb.html#detailed).
[b] Abbreviations for the texture classes are LFS, loamy fine sand; CL, clay loam; C, clay; SiL, silty loam
[c] Concentrations at 0-15 cm depth; P, Olsen-bicarbonate; pH, soil pH 1:1 soil/water.
[d] Level of agronomic P sufficiency in soil indicated by the letters L and M mean low and medium, respectively (MAFRD 2007).

3.3.2. Preceding Residue Management and Site Preparation

At each site-year there was uniform cereal grain production (wheat or barley) prior to corn test crop year, where grain was harvested and straw was left on the field. Sites were tilled in the fall of 2014 and 2015 using a tandem disk for conventional tillage and a Yetter® strip-till unit for strip-tillage. Strip-tillage was confined to 20-cm wide strips on 76-cm centres. Fall deep-band fertilizer treatments were applied with the strip-till unit on both the conventional and the strip-till plots. On conventionally tilled plots, the fall banded fertilizer treatment applications were superimposed with the strip-till unit after cultivation with a tandem disk. Fall fertilizer bands were marked with flags following application to enable planting corn rows directly over the bands in the spring. There was no spring tillage, only fall tillage; however, pre-plant burnoff herbicide was applied at Carman 2016, and post-plant burnoff herbicide was applied at Portage 2016 one day after planting (Appendix E.3).

3.3.3. Experimental Design and Treatments

The experimental design was a randomized split-block design with four replicates, taking into consideration the preceding tillage treatment, conventional and strip-till. The fertilizer treatments consisted of a control (no P added) and two rates of P (30 and 60 kg P_2O_5 ha^{-1}) in the form of monoammonium phosphate (MAP, 11-52-0) applied either in the fall as a deep band, 10-13 cm underneath the soil surface with the strip-till unit, or in the spring as a side band, 5 cm to the side and 2.5 cm below the seed, with the corn planter. The treatments are summarized as follows:

T1) Control (No P added)

T2) 30 kg P_2O_5 ha^{-1} MAP Spring side band (5 cm to the side and 2.5 cm below seed)

T3) 60 kg P_2O_5 ha^{-1} MAP Spring side band (5 cm to the side and 2.5 cm below seed)

T4) 30 kg P_2O_5 ha^{-1} MAP Fall deep band (10-13 cm deep)

T5) 60 kg P_2O_5 ha^{-1} MAP Fall deep band (10-13 cm deep)

Nitrogen fertilizer was broadcasted in the spring as SUPERU® in 2015 and AGROTAIN® treated urea in 2016 (Koch Fertilizer Canada, Brandon, MB) prior to corn planting and incorporated to a small degree with the corn planter. Sufficient N was applied to each plot to reach a target N supply of 250 kg N ha^{-1}, taking into account N in the fertilizer treatments and soil test nitrate-N concentrations. The corn hybrid Dekalb 26-28RIB Genuity® VTDoublePRO® (76-d RM) was planted 40-45 mm deep at 80,942 seeds ha^{-1} in 76-cm-wide rows using a four-row planter (John Deere 1755 4R drawn planter) at a speed of 3.2 km hr^{-1} in mid to late May (Table 3.2). This corn hybrid was chosen to represent a hybrid commonly grown by Manitoba farmers. Further, the hybrid was chosen based on corn heat units and the ability of the hybrid to reach maturity prior to the fall frost in the study area. In addition, commercial market availability of the hybrid for the duration of the study and yield potential were also considered. Each four-row plot measured 3 by 8 m. Appropriate herbicides were applied in the crop with a bike sprayer up to V4 growth stage and a backpack sprayer for the subsequent crop growth stages (Appendices E.3).

Table 3.2 Summary of planting and harvest dates for corn test crop in 2015 and 2016

Site-Year	Planting Date	Harvest Date
Carman 2015	May 25/15	October 16/15
Portage la Prairie 2015	May 26/15	October 19/15
Carman 2016	May 12/16[a]	October 05/16
Portage la Prairie 2016	May 16/16[b]	October 06/16

[a] Hand harvested due to wind damage and green snap on 2016 July 20.
[b] Hand harvested due to hail on 2016 Aug. 15 and black bird damage.

3.3.4 Weather Conditions

Accumulated corn heat units (CHU) were sufficient at all site-years for the corn hybrid to reach physiological maturity (2150 CHU) (Table 3.3). Total recorded growing season precipitation was below the required amount by the crop, considering a 7519 kg ha^{-1} corn crop uses about 530 mm in an average year, with corn water-use being the highest during reproductive phases of silking and pollination (July-Aug.) (Manitoba Corn Growers Association 2014). Although the corn crop had additional access to stored soil water, an overall measure of spring available soil moisture at each site-year indicated a growing season water balance deficit (Appendix J).

Table 3.3 Maximum, minimum and average air temperature, corn heat units (CHU), monthly and total precipitation, during the 2015 and 2016 growing seasons at Carman and Portage la Prairie, MB

Site-Year	Air Temperature				Precipitation					
	T_{max}	T_{min}	$T_{average}$	CHU_{total}	May	June	July	Aug.	Sep.	Total
	air temperature, C°				mm					
Carman 2015[a]	23.5	9.9	16.7	2686	7.6	75.3	109.3	47.3	42.0	296.9
Portage la Prairie 2015[a]	22.8	11	16.9	2840	4.3	64.1	170.2	82.9	20.8	368.5
Carman 2016[a]	22.9	10.4	16.7	2825	106.0	95.2	78.5	57.5	64.2	404.1
Portage la Prairie 2016[a]	22.7	11.7	17.2	2898	55.7	90.3	86.0	99.9	49.6	384.9

[a] Weather data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for Carman 2015 between May 25-October 16/2015, Portage la Prairie 2015 between May 26-Oct.19, Carman 2016 between May 12-Oct. 05 and Portage la Prairie 2016 between May 16-Oct. 06.

3.3.5 Early Season Crop Measurements

Early season biomass was collected by cutting 10 randomly selected plants at ground level from the two outside rows from each plot at V4 (based on visible leaf collar). Fresh samples were weighed and air-dried for a week. Biomass was then cut into smaller sections, oven dried at 60°C for 72 h, weighed, and ground to pass through a 1-mm screen.

Phosphorus concentration and uptake were determined for early season biomass collected at V4. Dried and ground samples were sent to AgVise Laboratories (Northwood, ND. USA) for nitric acid-peroxide digestion and P analysis by inductively couple plasma emission spectrometry. Plant P uptake was calculated from nutrient concentrations and oven-dried early season biomass weights.

Early season diffusion of phosphorus from soil was measured using Plant Root Simulator (PRS®) probes. The probes were placed in different zones of soil, depending on the tillage treatment. Two PRS probes were placed in each replicate of strip-till control plots, one in the untilled, residue-covered strip (between seedrows) and one in the tilled zone of the seedrow, where residue was removed and/or incorporated into the soil. Each replicate of conventional tillage control plots had one PRS probe placed in the seedrow only. The PRS probes were buried one week after planting, with the bottom of each probe placed at a depth of approximately 15 cm to correspond with P sampling depth for soils. The probes remained buried in the soil for 14 d, after which they were removed, washed and sent to Western Ag Innovations (Saskatoon, SK. Canada) for analysis.

Plant height was assessed by measuring from the ground to the extended tip of the most newly emerged leaf at V7 on 10 randomly selected plants from two middle rows of each plot.

3.3.6 Mid to Late Season Crop Measurements

The number of days from planting until the day when ≥50% of the plants in the two centre rows of each plot had reached the silking stage was recorded for each plot.

Late season cob moisture was assessed weekly, starting at dough (R4) stage until approximately one week prior to harvest. Moisture was measured using an Electrophysics® moisture meter with corn probe (Dutton, Ontario Model MT808C). Two readings were taken per cob, from six randomly selected cobs per plot. Final moisture reading was an average of 12 readings for each plot.

3.3.7 Late Season Crop Measurements

Grain yield and moisture content were determined by harvesting the two middle 8-m long rows from each plot using a plot combine (Wintersteiger Classic with HarvestMaster® Classic GrainGage system) in 2015. In 2016, strong winds at Carman on July 20 caused 42 to 68% of green snap in the corn plots (Appendix K.2b), while at Portage la Prairie on Aug. 15, a hail storm caused uniform damage to all the corn plots (Appendix K.3a,b). Therefore, in that year, grain yield and moisture content were determined by selecting and hand-harvesting 32 corn cobs and stationary threshing with a plot combine. At Carman in 2016, corn cobs were collected from plants where intra-row and inter-row competition were regarded as typical for a corn stand not damaged by green snap (i.e., cobs were collected from plants that had at least two undamaged plants on each side within a row and at least two undamaged plants in the two rows directly beside the sampled plant). For plants where two cobs developed, only the cob that was determined to be the main cob was collected. At Portage la Prairie in 2016, the hail damage was uniform in all plots, therefore 32 consecutive corn cobs were harvested from the two middle rows, 16 cobs from each row. Corn cobs were hand-harvested from each plot from an area equivalent to 4.05 m^2 (1/1000th of an acre) determined from plant stand counts at 4 wk after planting (Appendix F.1b). Grain yields were in both corn test crop years were adjusted to 155 g kg^{-1} moisture.

3.3.8 Statistical Analysis

Glimmix Procedure in SAS 9.4 was used for statistical analysis (SAS Institute, Inc. 2016). Treatment and site-year were considered fixed effects and block (site-year), and crop × block (site-year) were considered random effects. Conformity of the data was tested using the Shapiro-Wilk Statistic and assumptions regarding data conformity were tested using Proc Univariate. The Glimmix Procedure corrected for unequal variances for site-years with missing data. The Tukey-Kramer test was used to assign letter groupings for treatment least squares means ($P<0.05$). Days to silking did not follow a normal distribution and the datasets for this variable were transformed using the gamma distribution. Late season cob moisture was analyzed using compound symmetry (CS) structure for repeated measure analysis.

3.4. Results and Discussion

3.4.1. Early Season Biomass Yield (V4)

Analysis of variance indicated a significant site-year × tillage × fertilizer interaction for early season biomass (ESB) indicating that the tillage × fertilizer interaction was not consistent across site-years (Table 3.4). There were no differences in ESB between tillage systems for equivalent P treatments at any of the site-years. This lack of difference between tillage systems may be the result of strip-till and conventional till having similar degrees of soil disturbance within the zone near the seedrow. Therefore, the lack of soil disturbance in the inter-row zone appears to have had no significant effect on ESB. However, the three-way interaction indicated that there were some subtle differences in P response between the tillage systems. At Carman 2015, only the low rate of spring side banded P increased ESB significantly above the control in conventional tillage; whereas only the high rate of spring side banded P increased ESB relative to the unfertilized control in strip-till. Conversely, at Carman in 2016, only the high rate of spring side banded P significantly increased ESB in conventional tillage; whereas both rates of spring side banded P increased ESB in strip-till, relative to the unfertilized control. In contrast, at Portage in 2015 and 2016, none of the fertilized treatments produced ESB that was significantly greater than for the unfertilized controls.

Table 3.4 Early season biomass at V4: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			kg ha^{-1}				
Conventional	0	Control (no P)		202*Bb*[e]	312*Aab*	215*Bbcd*	176*Bb*	226
	30	Spring	SB	358*ABa*	408*Aa*	303*Bab*	200*Cab*	317
	60	Spring	SB	301*ABab*	393*Aa*	378*Aa*	243*Bab*	329
	30	Fall	DB	214*Ab*	273*Ab*	190*Acd*	274*Aab*	238
	60	Fall	DB	276*ABab*	323*Aab*	221*Bbcd*	231*ABab*	263
Strip-till	0	Control (no P)		196*Bb*	331*Aab*	133*Bd*	226*Bab*	221
	30	Spring	SB	280*Aab*	342*Aab*	266*Aabc*	251*Aab*	285
	60	Spring	SB	355*Aa*	366*Aab*	270*Aabc*	300*Aa*	323
	30	Fall	DB	295*ABab*	345*Aab*	169*Ccd*	243*BCab*	263
	60	Fall	DB	281*ABab*	349*Aab*	196*Bbcd*	313*Aa*	285
Conventional				270	342	261	225	275
Strip-till				281	346	207	267	275
	0	Control (no P)		199	321	174	201	224
	30	Spring	SB	319	375	285	226	301
	60	Spring	SB	328	379	324	272	326
	30	Fall	DB	254	309	180	259	250
	60	Fall	DB	279	336	208	272	274
Site-year				276	344	234	246	
ANOVA			Df			Pr>F		
Fert			4					<.0001*
Tillage			1					0.9462
Tillage*Fert			4					0.1126
Site-year			3					<.0001*
Site-year*Fert			12					0.0005*
Site-year*Tillage			3					0.0460*
Site-year*Tillage*Fert			12					0.0177*
Coeff Var (C.V.)								30
CONTRASTS								
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}								0.0062*
Spring SB vs. Fall DB								<.0001*

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-d Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Overall, when averaged across all sites years, tillage systems and P rates, deep banding P in the fall was not as effective as side banding at planting for increasing corn ESB relative to the unfertilized controls. However, at each of the two responsive site-years, the differences in ESB between fall deep banded P and spring side banded P were small and statistically insignificant. Nevertheless, the spring side banded P treatments resulted in more frequent increases in ESB compared to the unfertilized control, plus an overall increase in ESB, compared to fall deep banding. This may have been the result of more precise placement of P closer to the seed at the right time. Fall deep band placement was not as precisely placed relative to the seed and allowed more time for retention of P by the soil. In addition, the deep band used in our experiment was very deep (10-13 cm); therefore, the young corn plants may have been at a disadvantage early in the season since the root system had to reach the fertilizer at a greater depth.

Greater early season growth in response to spring side banded starter P has also been observed in no-till corn in Iowa (Bermudez and Mallarino 2002; Kaiser et al. 2005). Scharf (1999) reported larger responses to N and P starter fertilizers, compared with N-only starter at sites where STP concentrations were low, while Niehues et al. (2004) compared direct seed contact, dribble over-the-row, and a subsurface band placement of N-P-K-S starter fertilizers in a no-till corn production system and reported that early season dry matter increased regardless of fertilizer placement.

Lastly, when averaged across all site-years, tillage systems and methods of P application, ESB was greater from the higher rate of P fertilizer than from the lower rate of P.

3.4.2. Early Season Phosphorus Concentration in Plant Tissue (V4)

Early season P concentrations in plant tissue at V4 were not affected by tillage and soil disturbance (Table 3.5). Lack of response to tillage treatments could be the result of uniform corn development and similar ESB in both tillage systems. As mentioned before, the overall lack of response could be attributed to strip-till and conventional till having similar degrees of soil disturbance within the zone near the seedrow in our experiment. In contrast, studies looking at no-till systems have generally reported higher early season shoot P concentrations in plants compared with conventional systems (O'Halloran et al. 1986; McGonigle et al. 1990b, 1999; Galvez et al. 2001). In most cases, higher P concentrations under reduced-tillage are attributed to lower soil disturbance and the reduced effect on the AMF hyphal network (Evans and Miller 1990). However, McGonigle et al. (1990a) reported that although P absorption was reduced following soil disturbance, AMF colonization was not different among the disturbance treatments in their study.

Regardless of tillage system, the spring side banded P treatments increased early season plant P concentrations at V4, compared to those for the control. However, a site-year × fertilizer interaction resulted in differences in the effect of fertilizer treatment on P concentrations across site-years. At Carman in 2015 and 2016 both rates of spring side banded P treatments significantly increased early season P concentrations relative to the unfertilized control and the fall deep banded treatments. These results are consistent with the greater ESB reported with the spring side banded P at both of these site-years. At Portage 2015, only the high rate of spring side banded P increased P concentration relative to the control, while all banded P treatments significantly increased early season P concentration at Portage 2016. The greater frequency of response to spring side banded P compared to fall deep banded P is most likely the result of precise placement near the seed at planting, providing excellent access to nutrient for root uptake especially early in the season. As a result, when averaged across all site-years, tillage systems and rates, the concentrations of P in early season corn were greater for spring side banded P than for fall deep banded P. Also, the P concentrations were generally greater for the higher rate of P fertilizer than for the lower rate of P, when averaged across site-years, tillage systems and methods of P application.

Table 3.5 Early season phosphorus concentration in plant tissue at V4: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			g kg^{-1}				
Conventional	0	Control (no P)		3.2	4.4	3.1	2.7	3.3
	30	Spring	SB	4.4	4.6	3.6	3.8	4.1
	60	Spring	SB	5.3	5.0	4.2	4.2	4.7
	30	Fall	DB	3.6	4.5	3.1	3.3	3.6
	60	Fall	DB	3.6	4.5	3.2	3.8	3.8
Strip-till	0	Control (no P)		3.0	4.6	3.0	3.0	3.4
	30	Spring	SB	4.2	4.4	3.9	3.6	4.0
	60	Spring	SB	5.1	5.0	4.2	4.1	4.6
	30	Fall	DB	3.6	4.6	3.0	3.6	3.7
	60	Fall	DB	3.6	4.6	3.1	3.9	3.8
Conventional				4.0	4.6	3.4	3.6	3.9
Strip-till				3.9	4.6	3.4	3.7	3.9
	0	Control (no P)		3.1*Bc*[e]	4.5*Ab*	3.1*Bb*	2.9*Bc*	3.4
	30	Spring	SB	4.3*ABb*	4.5*Ab*	3.7*Ba*	3.7*Bab*	4.1
	60	Spring	SB	5.2*Aa*	5.0*Aa*	4.2*Ba*	4.2*Ba*	4.6
	30	Fall	DB	3.6*Bc*	4.5*Ab*	3.0*Bb*	3.5*Bb*	3.7
	60	Fall	DB	3.6*BCc*	4.6*Aab*	3.1*Cb*	3.9*Bab*	3.8
Site-year				4.0	4.6	3.4	3.6	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Tillage	1	0.9372
Tillage*Fert	4	0.8509
Site-year	3	0.0003*
Site-year*Fert	12	<.0001*
Site-year*Tillage	3	0.8900
Site-year*Tillage*Fert	12	0.9302
Coeff Var (C.V.)		20
CONTRASTS		
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}		<.0001*
Spring SB vs. Fall DB		<.0001*

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

3.4.3. Early Season Phosphorus Uptake (V4)

Corn P uptake was measured from nutrient concentrations and oven-dried early season biomass (ESB) weights. Therefore, early season P uptake at V4 reflected the general trends for increases in response to P fertilization already mentioned for ESB and P concentrations in tissue (Table 3.6). Once again, early season uptake of P was generally greater for spring side banded P than for fall deep banded P and also for the high rate of P than for the low rate of P. However, analysis of variance indicated a significant site-year × fertilizer interaction, where response to fertilizer rate and placement varied with site-year.

At Carman 2015, both spring side banded P treatments and the high rate of fall deep banded P increased early season P uptake relative to the unfertilized control. At Portage 2016, only the high rate of P, regardless of placement and timing of application, increased early season P uptake compared to unfertilized control. Both rates of spring side banded P, but not deep banded P, significantly increased early season P uptake at Carman 2016, while at Portage 2015 only the high rate of spring side banded P effectively increased P uptake, relative to the unfertilized controls and fall deep banded P treatments. Similar to early season P concentrations in plant tissue reported earlier, spring side banded P increased early season P uptake more frequently than deep banded P.

Similarly, in Kansas, Schwab et al. (2006) compared surface broadcast, side band and deep band (15 cm) fertilizer placements and showed that with 20 kg P ha^{-1} there was no difference in P uptake between the check plot and the deep band treatment, while the surface broadcast and side banded P treatments outperformed the deep banded P placement. In our study, the high rate of fall deep banded P increased P uptake only at Carman 2015 and Portage 2016, where soil textures were relatively coarse (Table 3.3). The response to fall deep banded P at these loamy-sand and silty-loam soils may have been due to faster, deeper rooting of the corn crop. However, it is important to note that roots are not always impacted by nutrient level, placement and soil depth (Fernández 2016).

Table 3.6 Early season phosphorus uptake at V4: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			kg ha^{-1}				
Conventional	0	Control (no P)		0.6	1.4	0.7	0.5	0.8
	30	Spring	SB	1.6	1.9	1.1	0.8	1.3
	60	Spring	SB	1.6	2.0	1.6	1.0	1.5
	30	Fall	DB	0.7	1.2	0.6	0.9	0.9
	60	Fall	DB	1.0	1.5	0.7	0.9	1.0
Strip-till	0	Control (no P)		0.6	1.5	0.4	0.7	0.8
	30	Spring	SB	1.2	1.5	1.0	0.9	1.2
	60	Spring	SB	1.8	1.8	1.1	1.2	1.5
	30	Fall	DB	1.1	1.6	0.5	0.9	1.0
	60	Fall	DB	1.0	1.6	0.6	1.2	1.1
Conventional				1.1	0.9	1.6	0.8	1.1
Strip-till				1.1	0.7	1.6	1.0	1.1
	0	Control (no P)		0.6*Bc*[e]	1.4*Ab*	0.5*Bb*	0.6*Bb*	0.8
	30	Spring	SB	1.4*ABa*	1.7*Aab*	1.1*BCa*	0.8*Cab*	1.3
	60	Spring	SB	1.7*ABa*	1.9*Aa*	1.4*BCa*	1.1*Ca*	1.5
	30	Fall	DB	0.9*Bbc*	1.4*Ab*	0.5*Bb*	0.9*Bab*	0.9
	60	Fall	DB	1.0*Bb*	1.5*Ab*	0.7*Bb*	1.1*Ba*	1.1
Site-year				1.1	1.6	0.8	0.9	
ANOVA			Df			Pr>F		
Fert			4					<.0001*
Tillage			1					0.9000
Tillage*Fert			4					0.0755
Site-year			3					0.0001*
Site-year*Fert			12					<.0001*
Site-year*Tillage			3					0.3435
Site-year*Tillage*Fert			12					0.0540
Coeff Var (C.V.)								45
CONTRASTS								
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}								<.0001*
Spring SB vs. Fall DB								<.0001*

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

3.4.4. Plant Root Simulator (PRS ®) Probe Soil P Supply

In 2015, Portage had significantly greater rates of P supply rates than at Carman, during their respective burial times (Table 3.7a). However, tillage system and location of the probes within the strip-till system did not significantly affect P diffusion in either site-year. Further, P supply was not affected by a significant interaction between site-year x tillage system and probe location.

In 2016, Portage had significantly greater rates of P supply rates than at Carman, during their respective burial times (Table 3.7b). This may be due to greater STP concentrations at Portage 2016 (14 mg kg^{-1}) compared to Carman 2016 (5 mg kg^{-1}). Tillage system and location of the probes within the strip-till system did not significantly affect P diffusion. Furthermore, P supply was not affected by a significant interaction between site-year x tillage system and probe location.

Due to fall deep banding of KCl in seedrow zone at Carman 2015, both tillage systems at this site had greater K supply rates within the seedrow than in the strip-till residue zone. However, K supply rates in the seedrow were not statistically different for conventional tillage when compared to strip-tillage. Further, at Carman 2015 only, S supply rates were smaller in the seedrow zone for both tillage systems than in the strip-till residue zone. This may be attributed to the movement of pre-plant broadcast S fertilizer away from the seedrow by the planters' row cleaners during planting. However, similar to K, the S supply rates in the seedrow were similar for both tillage systems. There was also a greater supply of K in the strip-till residue row compared to seedrow in the conventional tillage system. Further, K supply rates were greater at

Carman 2016 compared to Portage 2016, most likely caused by fall deep banding KCl in the seedrow at Carman 2016.

Zinc supply rates were greater in conventional tillage seedrow compared to strip-till seedrow; however, the supply of Zn measured in the strip-till residue row was not significantly different from that in the conventional tillage seedrow.

Therefore, similarities between the nutrient supply rates from soil for the two tillage systems in 2015 and 2016 support our earlier observations that the differences in early season plant growth and early season P uptake were due to fertilizer placement and rate, rather than tillage (Table 3.4, 3.5).

Table 3.7a PRS™ probe nutrient supply rates (in-situ burials): effect of tillage practices and probe location at corn fertility trials at Carman and Portage La Prairie, MB in 2015

Site-year	Tillage Treatment and Probe Location	Total N	NO_3-N	NH_4-N	Ca	Mg	K	P	Fe	Mn	Cu	Zn	B	S	Pb	Al	Cd[a]
		Nutrients (µg/10cm²/burial period)[b]															
Group site-year means[c]																	
Carman 2015		634b[d]	579b	55a	1885	363b	160	3b	67a	54	0.8b	0.9	0.3	134	1.1	27	0
Portage 2015		766a	760a	6b	1974	680a	47	5a	4b	4	1.2a	0.7	0.2	23	1.3	12	0
Group tillage treatment and probe location means[c]																	
All sites	Conventional tillage seedrow	656	630	26	1975	535	124	5	35	29	0.9	0.7	0.3	53	1.3	24	0
	Strip-tillage seedrow	659	634	25	1886	500	110	4	40	39	1.2	0.9	0.2	62	1.3	17	0
	Strip-tillage residue zone	785	745	40	1928	530	75	3	32	19	0.9	0.8	0.3	121	1.0	17	0
Group site-year × tillage treatment and probe location means[c]																	
Carman 2015	Conventional tillage seedrow	566	519	46	1882	352	203a	4	67	55ab	0.7	0.8	0.3	79b	1.0a	36a	0
	Strip-tillage seedrow	637	590	47	1847	361	183a	3	74	73a	0.9	0.9	0.2	106b	1.3bc	22bc	0
	Strip-tillage residue zone	700	629	72	1925	376	93b	2	60	35b	0.7	0.9	0.5	216a	1.0b	24c	0
Portage 2015	Conventional tillage seedrow	745	740	5	2068	718	46b	5	4	3c	1.1	0.6	0.3	27b	1.5d	12d	0
	Strip-tillage seedrow	681	677	4	2009	638	36b	6	5	6c	1.4	0.9	0.1	19b	1.3cd	12cd	0
	Strip-tillage residue zone	871	862	9	1847	684	58b	4	4	3c	1.1	0.6	0.1	25b	1.0d	11d	0
ANOVA	**Df**	**Pr>F**															
Tillage and probe location	2	0.0973	0.1173	0.4409	0.57	0.5037	0.0653	0.2995	0.4712	0.0101*	0.0804	0.2374	0.4989	0.0174*	0.3242	0.0089*	N/A
Site-year	1	0.022*	0.0016*	0.0003*	0.1981	0.0024*	<.0001*	0.0048*	0.0002*	<.0001*	0.0428*	0.5271	0.1422	0.0155*	0.2878	<.0001*	N/A
Site-year* Tillage and probe location	2	0.5107	0.412	0.6777	0.2364	0.3866	0.0115*	0.8008	0.5884	0.0265*	0.8651	0.5648	0.1888	0.0197*	0.3242	0.0061*	N/A
Coeff Var (%)		21	23	116	9	36	74	49	98	103	39	43	89	111	33	51	N/A

[a] All reported values were below the Method Detection Limits (mdl) of 0.2 probe supply rate (µg/10cm²/burial period).
[b] Burial period at Carman 2015 from June 01-15 and at Portage 2015 from June 03-17.
[c] Least square means (LSmeans) calculated by Proc Glimmix.
[d] a-d Least square mean values followed by the same letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
* Significant at $P < 0.05$.

Table 3.7b PRS™ probe nutrient supply rates (in-situ burials): effect of tillage practices and probe location at corn fertility trials at Carman and Portage La Prairie, MB in 2016

Site-year	Tillage Treatment and Probe Location	Nutrients															
		Total N	NO_3-N	NH_4-N	Ca	Mg	K	P	Fe	Mn	Cu	Zn	B	S	Pb	Al	Cd[a]
		($\mu g/10cm^2$/burial period)[b]															
Group site-year means[c]																	
Carman 2016		726a[d]	704a	22a	1838b	403b	104a	5b	81a	42a	0.9	4.0a	0.9	28	0.8b	33a	0
Portage 2016		481b	480b	1b	2370a	574a	51b	26a	10b	4b	1.1	2.2b	1.1	45	1.5a	12b	0
Group tillage treatment and probe location means[c]																	
All sites	Conventional tillage seedrow	555	543	12	2251a	512	64b	15	60a	28a	1.1	3.4a	1.5a	34	1.3	26a	0
	Strip-tillage seedrow	580	572	8	2101b	482	79ab	15	46a	18ab	1.0	2.5b	1.1ab	25	1.1	25a	0
	Strip-tillage residue zone	675	661	14	1961b	473	90a	15	29b	22b	0.9	3.4a	0.5b	51	1.1	18b	0
Group site-year × tillage treatment and probe location means[c]																	
Carman 2016	Conventional tillage seedrow	664	641	23	1947	426	81	6	110a	52	1.1	4.5	1.4	18	1.0	38a	0
	Strip-tillage seedrow	750	735	15	1890	411	108	4	82a	41	0.9	3.3	1.2	23	0.8	38a	0
	Strip-tillage residue zone	765	737	28	1678	373	122	5	50b	32	0.7	4.4	0.3	44	0.5	24b	0
Portage 2016	Conventional tillage seedrow	446	445	1	2554	597	46	25	11c	4	1.1	2.3	1.6	51	1.5	13b	0
	Strip-tillage seedrow	411	410	1	2312	553	51	26	10c	4	1.1	1.7	1.1	27	1.5	12b	0
	Strip-tillage residue zone	585	584	1	2244	572	57	26	8c	3	1.0	2.5	0.8	59	1.6	12b	0
ANOVA	Df	Pr>F															
Tillage and probe location	2	0.2916	0.2823	0.6908	0.0006*	0.0728	0.0265*	0.9379	0.0011*	0.0472*	0.4704	0.0231*	0.0248*	0.0932	0.7161	0.0056*	N/A
Site-year	1	0.0172*	0.0172*	0.0451*	0.0005*	0.0007*	0.0003*	0.0004*	<.0001*	0.0010*	0.3467	0.0016*	0.4795	0.1088	0.0136*	0.0024*	N/A
Site-year* tillage and probe location	2	0.5674	0.4844	0.7072	0.2280	0.2437	0.2159	0.8179	0.0021*	0.0569	0.5593	0.6357	0.6198	0.4329	0.4382	0.0148*	N/A
Coeff Var (%)		32	32	167	15	20	42	75	94	98	36	40	68	68	53	58	N/A

[a] All reported values were below the Method Detection Limits (mdl) of 0.2 probe supply rate ($\mu g/10cm^2$/burial period).
[b] Burial period at Carman 2016 from May 26-June 08 and at Portage 2016 from May 30-June 12.
[c] Least square means (LSmeans) calculated by Proc Glimmix.
[d] a-c Least square mean values followed by the same letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

3.4.5. Early Season Plant Height (V7)

Tillage had no effect on plant height at V7; the strip-till system produced plants that were the same height as plants in conventional tillage (Table 3.8). This is contrary to Minnesota corn-soybean studies (Vetsch and Randall 2002) and a Florida cotton study (Wiatrak et al. 2007) where greater overall plant heights were reported in conventional tillage compared to plants in strip-tillage. Alternatively, Boomsma et al. (2006) reported that mean plant heights are not always lower in no-till systems since other factors such as moisture availability, fertilizer application and overall crop growth rate can also influence plant height.

A site-year × fertilizer interaction showed that the effect of P fertilization on plant height at V7 varied with site-year (Table 3.8). Spring side banded P increased plant height at the high rate of P at Carman in 2015 (20%) and at both rates of P at Carman 2016 (30%), relative to the unfertilized controls. Similar responses of early season plant height to starter fertilizer were reported by Mascagni and Boquet (1996), Bundy and Andraski (1999), Cromley et al. (2006) and Kaiser et al. (2016). However, none of the fertilized treatments increased plant height over the unfertilized control at Portage 2015 and only the low rate of fall deep banded P increased plant height at Portage 2016 (26%). When averaged across all site-years, tillage treatments and P rates, plant height was slightly greater (9 cm) for spring side banded P than for fall deep banded P. However, plant height was similar for both rates of P when averaged across site-years, tillage systems, and methods of P application.

Table 3.8 Early season plant height at V7: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			cm				
Conventional	0	Control (no P)		105	109	146	102	115
	30	Spring	SB	121	129	145	106	125
	60	Spring	SB	124	147	147	112	132
	30	Fall	DB	114	106	140	119	120
	60	Fall	DB	111	109	145	111	119
Strip-till	0	Control (no P)		103	100	141	106	112
	30	Spring	SB	126	131	147	115	130
	60	Spring	SB	127	135	149	124	134
	30	Fall	DB	112	102	147	144	126
	60	Fall	DB	121	110	137	110	120
Conventional				115	145	120	110	122
Strip-till				118	144	116	120	124
	0	Control (no P)		104*Bb*[e]	143*Aa*	104*Bb*	104*Bb*	114
	30	Spring	SB	123*BCab*	146*Aa*	130*ABa*	110*Cb*	127
	60	Spring	SB	125*BCa*	148*Aa*	141*ABa*	118*Cab*	133
	30	Fall	DB	113*BCab*	143*Aa*	104*Cb*	131*ABa*	123
	60	Fall	DB	116*Bab*	141*Aa*	110*Bb*	110*Bb*	119
Site-year				116	144	118	115	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Tillage	1	0.4977
Tillage*Fert	4	0.6960
Site-year	3	<.0001*
Site-year*Fert	12	<.0001*
Site-year*Tillage	3	0.3372
Site-year*Tillage*Fert	12	0.9282
Coeff Var (C.V.)		17
CONTRASTS		
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}		0.6768
Spring SB vs. Fall DB		0.0002*

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

3.4.6. Days from Planting to Silking (R1)

Tillage had no effect on days from planting to silking, and the strip-till corn reached this stage of maturity on the same day as corn in conventional tillage (Table 3.9).

Overall, all site-years reached silking on different dates; however, on average in 2015, both sites reached silking 9 d earlier compared to 2016 site-years, regardless of tillage system or fertilizer treatment. The reason for this difference between years was that the corn crop was planted two weeks earlier in 2016 compared to 2015, exposing the corn to colder soil and air temperatures at the start of the growing season and extending the time from planting to silking.

A site-year × fertilizer interaction showed that banded P reduced days to silking only at Carman 2015 and Carman 2016 relative to the unfertilized controls (Table 3.9, Appendix G.2). At Carman 2015, all fertilized treatments reduced days to silking by 2-3 d relative to the unfertilized control. At Carman 2016, only the spring side banded P treatments reduced days to silking (3 d), compared to the unfertilized control. The advancement in maturity at Carman 2015 and 2016 corresponds with greater early season biomass and plant height response to P fertilization compared to the unfertilized controls. In contrast, maturity responses to P fertilization were not observed at Portage in 2015 and 2016, where early season biomass and plant height responses to banded P were also lacking or infrequent. Therefore, at both Portage site-years, the fertilized treatments reached silking on the same day as the unfertilized plots, regardless of tillage system. Nevertheless, when averaged across all site-years, tillage treatments and P rates, days from planting to silking were slightly lower for spring side banded P than for fall deep banded P. However, days to silking were similar for both rates of P when averaged across site-years, tillage systems, and methods of P application.

Other studies have also shown inconsistent phenological responses to starter fertilizer. Starter fertilizer reduced days to tassel emergence by 4 to 5 d in Missouri (Scharf 1999) and Illinois (Bullock et al. 1993) compared to no starter plots. Conversely, other studies showed that starter fertilizer had no effect on the number of days to reach physiological maturity (R6) (Cromley et al. 2006) or the number of days in the grain fill period (Gordon et al. 1997).

Table 3.9 Days from planting to silking: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	— kg ha^{-1} —			DAP[e]				
Conventional	0	Control (no P)		64	65	74	71	69
	30	Spring	SB	63	64	73	70	67
	60	Spring	SB	62	64	73	70	67
	30	Fall	DB	62	65	77	70	68
	60	Fall	DB	63	65	74	70	68
Strip-till	0	Control (no P)		65	65	78	71	69
	30	Spring	SB	63	65	72	70	67
	60	Spring	SB	62	64	73	70	67
	30	Fall	DB	63	64	75	70	68
	60	Fall	DB	63	64	75	70	68
Conventional				63	65	74	70	68
Strip-till				63	64	75	70	68
	0	Control (no P)		65*Ca*[f]	65*Ca*	76*Aa*	71*Ba*	69
	30	Spring	SB	63*Db*	64*Ca*	73*Ab*	70*Ba*	67
	60	Spring	SB	62*Db*	64*Ca*	73*Ab*	70*Ba*	67
	30	Fall	DB	62*Db*	64*Ca*	76*Aa*	70*Ba*	68
	60	Fall	DB	63*Db*	65*Ca*	75*Aa*	70*Ba*	68
Site-year				63	65	75	70	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Tillage	1	0.4668
Tillage*Fert	4	0.2921
Site-year	3	<.0001*
Site-year*Fert	12	<.0001*
Site-year*Tillage	3	0.6426
Site-year*Tillage*Fert	12	0.1410
Coeff Var (C.V.)		7
CONTRASTS		
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}		0.4508
Spring SB vs. Fall DB		0.0003*

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] DAP, days after planting.
[f]A-D Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

3.4.7. Late Season Cob Moisture (R4 – Harvest)

Late season cob moisture data was not combined across sites and each site-year was analyzed separately because sampling dates and frequency of sampling varied between site-years.

Cob moisture was not affected by P or tillage at Carman 2015 or Portage 2016 (P>0.05, Fig.3.1, Appendix G.3a,d). However, cob moisture was slightly lower for strip-tillage than for conservation tillage for one date at Portage 2015 (P=0.0070) and side banded P treatments decreased late season cob moisture for three dates at Carman 2016 (P=0.0368).

A tillage × date interaction at Portage 2015 (P= 0.0070, Fig.3.1, Appendix G.3b) showed that cob moisture was 3 g kg^{-1} lower in strip-till corn, compared to corn in conventional tillage on 2015 Oct. 13. Although this small difference was measured on the last sampling date before harvest, grain moisture differences due to tillage were not observed at Portage 2015 when the corn was harvested 1 wk later.

A fertilizer × date interaction (P= 0.0368, Fig.3.1, Appendix G.3c) showed that cob moisture declined with the application of spring side banded P on three sampling dates at Carman 2016. On the fourth (2016 Sep. 08) and sixth (2016 Sep.20) sampling dates only, the high rate of spring side banded P significantly reduced moisture by 3 g kg^{-1}, relative to the unfertilized control. However, on both of these dates, the moisture content for the low rate of spring side banded P was not statistically different from the high rate of spring side banded and fall deep banded P treatments. On the fifth sampling date (2016 Sep. 13), both spring side banded P treatments reduced cob moisture by an average of 4.5 g kg^{-1} relative to the unfertilized control and fall deep banded P treatments.

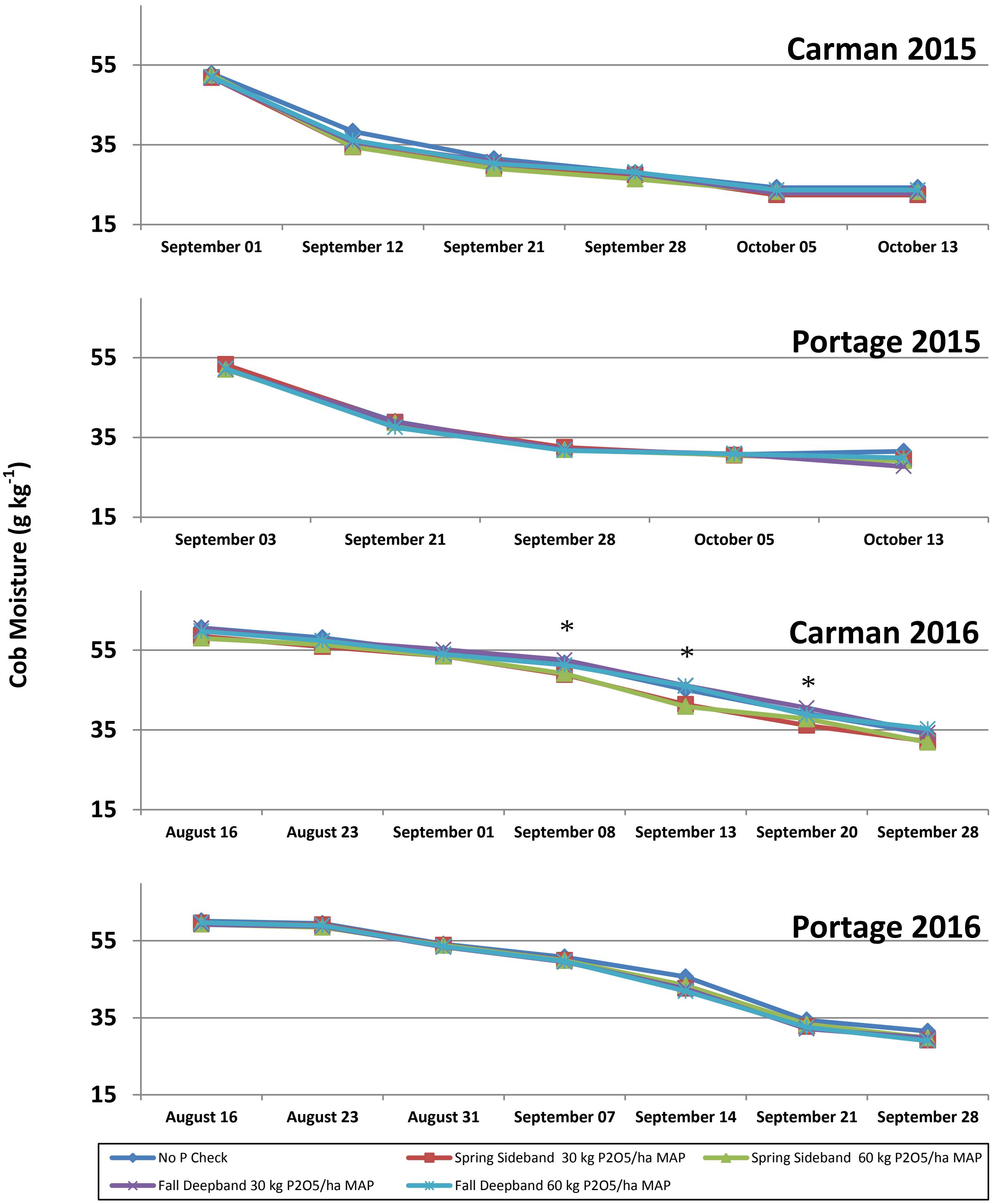


Figure 3.1. Late season cob moisture as affected by spring side banded P (5 cm below the seed × 2.5 cm to the side) and deep banded P (10-13 cm), measured from R4 until harvest (fertilizer × date) at Carman 2015, Portage 2015, Carman 2016 and Portage 2016. Asterisks (*) indicate significant differences between fertilizer treatments (P<0.05).

Overall, producers will favour P fertilization practices that accelerate the rate of dry-down and ultimately reduce grain moisture content because these allow for a more timely harvest, especially when racing against the threat of fall frost (Nielsen 2013). Therefore, spring side banded P may be a more efficient management system that allows for quicker dry-down when compared with fall deep banded P, especially in years when the corn crop is planted early and/or on fine textured soils.

3.4.8. Grain Moisture at Harvest

At harvest, tillage had no effect on grain moisture and strip-till corn had the same grain moisture as corn in conventional tillage (Table 3.9). Our results are similar to a study in southern Wisconsin, where corn grown in a fall strip-till system had the same grain moisture content as corn grown in a chisel system (Wolkowski 2000).

Fertilization reduced grain moisture only at Carman 2016 and Portage 2016, resulting in a significant site-year × fertilizer interaction. However, grain moisture at Carman 2015 and Portage 2015 was not influenced by P fertilization. At Carman 2016, both rates of spring side banded P decreased grain moisture at harvest by an average of 1.4 g kg^{-1} compared to the unfertilized control and both rates of fall deep banded P. Also, all P fertilization treatments significantly reduced grain moisture at Portage 2016, by an average of 1.4 g kg^{-1} compared to the unfertilized control. Since grain moisture reduction was observed only in 2016, it is reasonable to suggest that earlier planting and harvest at Carman 2016 and Portage 2016 may have been responsible for the grain moisture response to banded P. However, it is uncertain as to which site-year factors contributed to the differences in grain moisture response to fall deep banded P for Carman 2016 and Portage 2016. When averaged across all site-years, tillage treatments and P rates, grain moisture at harvest was similar for spring and deep banded P treatments and both rates of P.

Table 3.10 Grain moisture at harvest: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	— kg ha^{-1} —			— g kg^{-1} —				
Conventional	0	Control (no P)		20.9	23.2	25.4	22.4	23.0
	30	Spring	SB	19.9	23.4	24.1	21.1	22.1
	60	Spring	SB	19.8	23.0	24.4	21.2	22.1
	30	Fall	DB	20.2	23.4	25.5	20.3	22.4
	60	Fall	DB	20.4	22.9	25.0	20.7	22.2
Strip-till	0	Control (no P)		20.5	23.6	26.3	21.8	23.1
	30	Spring	SB	19.3	23.5	24.1	20.8	21.9
	60	Spring	SB	19.8	23.3	23.9	20.4	21.8
	30	Fall	DB	19.9	23.0	25.1	20.9	22.2
	60	Fall	DB	20.0	23.3	25.6	20.2	22.3
Conventional				20.2	23.2	24.9	21.1	22.4
Strip-till				19.9	23.3	25.0	20.8	22.3
	0	Control (no P)		20.7*Da*[e]	23.4*Ba*	25.9*Aa*	22.1*Ca*	23.0
	30	Spring	SB	19.6*Ca*	23.5*Aa*	24.1*Ab*	20.9*Bb*	22.0
	60	Spring	SB	19.8*Ba*	23.1*Aa*	24.2*Ab*	20.8*Bb*	22.0
	30	Fall	DB	20.1*Ca*	23.2*Ba*	25.3*Aa*	20.6*Cb*	22.3
	60	Fall	DB	20.2*Ca*	23.1*Ba*	25.3*Aa*	20.4*Cb*	22.2
Site-year				20.1	23.3	24.9	21.0	
ANOVA			Df			Pr>F		
Fert			4					<.0001*
Tillage			1					0.6919
Tillage*Fert			4					0.8921
Site-year			3					<.0001*
Site-year*Fert			12					0.0126*
Site-year*Tillage			3					0.7966
Site-year*Tillage*Fert			12					0.6480
Coeff Var (C.V.)								10
CONTRASTS								
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}								0.6580
Spring SB vs. Fall DB								0.0559

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-D Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Once again, these variations in response to starter fertilizer across site-years are reflected in other research. Mascagni and Boquet (1996) reported much greater reductions in grain moisture at harvest (7 to 14 g kg^{-1}) with the application of in-furrow fertilizer, while Kaiser et al. (2016) observed a much smaller 2 g kg^{-1} reduction. In contrast, Scharf (1999) reported no differences in grain moisture due to starter fertilizer.

Nevertheless, reduced grain moisture speeds up the harvest progress, decreases the need for artificial drying after harvest and the need for larger dryer capacity (Nielsen 2013). According to Kaiser et al. (2016), even a small reduction in grain moisture at harvest, such as the reduction observed in our experiment can help reduce drying costs and as a result, potentially cover the cost of starter fertilizer, even in cases where starter fertilizer application does not influence net return with an increase in grain yield.

3.4.9. Grain Yield (Harvest)

Averaged across all site-years, tillage system and P rates, spring side banded P increased grain yield by an average of 467 kg ha^{-1} relative to the unfertilized control and out-yielded the fall deep banded treatments by 470 g kg^{-1} (Table 3.11). However, similar to other mid and late season measurements, overall average grain yields were similar for both rates of applied P. Grain yields for fall deep banded treatments were not significantly greater than for the unfertilized controls. Positive yield response to starter fertilizer placed in a side band has been documented in many studies (Scharf 1999; Wolkowski 2000; Bermudez and Mallarino 2002). On the other hand, Wortmann et al. (2006) reported the most profitable grain yield response to starter fertilizer in irrigated corn, and only where soil test P levels were low. However, in some cases the excellent positional and chemical nutrient availability of the starter fertilizer and early season responses do not translate into profitable yield increase at the end of the season (Bullock et al. 1993; Bundy and Andraski 1999; Bermudez and Mallarino 2004).

Table 3.11 Grain yield at harvest: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	—— kg ha^{-1}——					kg ha^{-1}		
Conventional	0	Control (no P)		9908	7400	11752	7337	9099
	30	Spring	SB	10326	7027	12278	8063	9423
	60	Spring	SB	10500	7141	12531	8029	9550
	30	Fall	DB	10115	7316	11515	8000	9236
	60	Fall	DB	10118	7295	11618	7523	9139
Strip-till	0	Control (no P)		9958	7313	11428	8069	9192
	30	Spring	SB	10585	8047	12346	8013	9748
	60	Spring	SB	10682	7674	12233	8322	9728
	30	Fall	DB	9992	7254	11093	7578	8979
	60	Fall	DB	10372	7200	11546	7736	9214
Conventional				10193	7236	11939	7790	9290
Strip-till				10318	7497	11729	7944	9372
	0	Control (no P)		9933	7357	11590	7703	9146*b*[e]
	30	Spring	SB	10455	7537	12312	8038	9586*a*
	60	Spring	SB	10591	7408	12382	8175	9639*a*
	30	Fall	DB	10053	7285	11304	7789	9108*b*
	60	Fall	DB	10245	7247	11582	7630	9176*b*
Site-year				10255*B*[e]	7367*C*	11834*A*	7867*C*	

ANOVA	Df	Pr>F
Fert	4	0.0002*
Tillage	1	0.6284
Tillage*Fert	4	0.4123
Site-year	3	<.0001*
Site-year*Fert	12	0.5838
Site-year*Tillage	3	0.7742
Site-year*Tillage*Fert	12	0.7906
Coeff Var (C.V.)		21
CONTRASTS		
30 kg P_2O_5 ha^{-1} vs. 60 kg P_2O_5 ha^{-1}		0.5617
Spring SB vs. Fall DB		<.0001*

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping; A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

With the potential for less positional and chemical availability, yield response to deep banded P is less frequently documented in literature than yield response to side banded P. However, Vyn (2008) observed no differences between deep banded and broadcast P treatments in four out of five years. During the one year where a small benefit from deep banded P was observed, abundant rain and favourable soil moisture conditions stimulated root growth and consequently uptake in the deep band zone, resulting in increased yields. In studies where yield responses to deep banded P are measured, increases are generally small and typically observed in reduced tillage systems (Randall and Hoeft 1988). Furthermore, Schwab et al. (2006) reported that although deep banded P improved early season corn growth, final corn grain yields were not affected, while grain yield of sorghum was generally greater with deep banded P application. They concluded that differences in root structure and morphology allow certain crops, such as sorghum, to be more responsive to deep banded P compared to other crops, such as corn. Therefore, creating and maintaining soil conditions that are optimal for root development may be important in improving crop's accessibility to deep banded fertilizers.

Across all site-years in our study, strip-till corn yielded the same as corn in conventional tillage. Lack of differences in corn yields between tillage treatments suggests that growers can realize the benefits of a conservation tillage practice, such as strip-till, without having to sacrifice yield or maturity at harvest. Similar results were reported by Vyn and Raimbault (1992), where strip-till corn yields were as high as those in conventional tillage, and greater than no-till corn yields. Swan et al. (1994), McGonigle et al. (1999) and Schwab et al. (2006) also reported minimal tillage impacts on corn yields in no-till corn management system. In contrast, (Fernández and White 2012) reported that strip-till residue management system improved nutrient uptake and enhanced grain fill closer to the corn ear tip, resulting in a greater number of kernels per row and greater yield in strip-till corn compared to no-till corn.

3.5. Conclusions

The results of our study suggest that starter fertilizer placed in close proximity to the seed at planting will likely be beneficial in a northern corn production area, regardless of whether the corn is planted in a conventional till or strip-till system. Spring side banded P treatments increased early season biomass, early season P concentrations in plant tissue and P uptake at V4, relative to the unfertilized control. Further, starter fertilizer reduced days to silking and reduced grain moisture at harvest. However these responses varied with site-year. Corn response to fall deep banded P was not as consistent for early, mid and late season measurements and spring side banded P often out-performed the fall deep banded application. Averaged over all site-years, spring side banded P out-yielded the control and both fall deep banded P treatments. Furthermore, the higher rate of P fertilizer resulted in greater early season response than the low rate of P, while mid and late season measurements were similar for both rates of applied P when averaged across all site-years, tillage systems and methods of P application.

Generally, tillage had no effect on early, mid and late season measurements and corn planted in strip-till yielded the same as corn planted in conventional tillage, and had similar grain moisture at harvest. Therefore, strip-till systems can be an effective strategy for maintaining corn productivity and protecting soil from erosion in northern corn production areas, such as Manitoba. Further, tillage seemed to have no effect on the rate of soil P supply to corn seedlings; therefore differences in early season growth and P uptake were likely due to the beneficial placement of starter fertilizer in close proximity to the seed. Although we did not perform an economic analysis on the two tillage treatments in our study, considerable fuel and labour savings could potentially be realized in the strip-till treatment due to reduced trips over the field. In comparison, a farm-scale conventional tillage operation is generally performed twice, once in the fall and again in the spring. Overall, strip-till in combination with starter fertilizer, appears to be a viable conservation tillage alternative to conventional tillage in Manitoba, where cold and wet soils at planting are a risk to timely planting and vigorous early season growth.

4. SYNTHESIS

4.1. Overall Contribution to Knowledge

Corn growers in northern, non-traditional corn producing areas such as Manitoba are likely to grow canola in their rotation, with many farmers also practicing some form of conservation tillage. These agricultural practices present special challenges for successful corn production given Manitoba's relatively short growing season and cold soils at planting. Therefore, as corn production in Manitoba expands, local farmers are interested in starter fertilizer use to improve early season plant growth, advance maturity and potentially produce greater grain yields at harvest.

Both of our research studies showed that side banded starter fertilizer placed in close proximity to the seed at planting was beneficial in our northern corn production system and allowed the corn plants to have excellent access to P. This was especially important early in the season, at a time when P availability, root growth and plant uptake were limited due to our cold soils. Further, our research showed that in our environment, where the growing season is relatively short and hybrid maturity is marginally sufficient, starter fertilizer accelerated maturity, increased grain yields and reduced moisture at harvest. These starter fertilizer benefits were most evident if corn was planted after canola, while tillage system had no influence on response to starter P, final grain yield and grain moisture. Accelerated crop maturity and lower grain moisture at harvest are particularly important in our province because farmers are racing against the threat of fall frost and poor harvesting conditions.

In our studies, an increase in grain yield was generally observed when early season biomass increased and days to silking were reduced in response to starter fertilizer, regardless of STP, soil temperature and planting date. However, with an earlier planting date, the grain moisture decrease in response to starter fertilizer was greater when compared to later planting dates. Therefore, as long as the starter fertilizer response is observed early in the season and continues on through maturity, it is likely that in our region it will result in increased yields, potentially increasing profitability for corn growers.

4.2. Benefits for Corn Growers

Based on our findings, farmers can realize the benefits of starter fertilizer in the year of application. Net returns could be influenced not only by increased yields, but also with reduction in grain moisture at harvest. Even a small reduction in grain moisture at harvest can decrease the need for artificial drying after harvest, speed up the overall harvest progress and reduce the need for larger dryer capacity.

A combination of improving accessibility to earlier planting dates (i.e., planting into colder soils) and late maturing corn hybrids could further compound the benefits of starter fertilizer. The positive early season response to starter fertilizer and accelerated maturity could help the crop realize more of its yield potential, prior to the killing fall frost. Further, a greater yield potential with late relative maturity hybrids and the opportunity to extend the growing season with earlier planting dates could allow farmers to reduce their cropping risk and improve production.

4.3. Future Studies

The two studies presented in this thesis should also be discussed in light of opportunities for refinements to future studies. Corn root collection and assessment of arbuscular mycorrhizal colonization at V4 may have been done too late to detect differences which may have been present earlier in the growing season. As the season progressed and the crop matured, detection of significant percent colonization differences among corn roots following different crop rotations may have diminished, and the inhibitory effect of canola on percent corn root colonization may have disappeared by V4 (visible leaf collar stage). Therefore, sampling at an earlier stage, such as the V3 stage may be more appropriate since P deficiency symptoms were more pronounced earlier on. Further, arbuscular mycorrhizal fungi colonization was not assessed in the cereal residue management study and there were no tillage treatments in the canola vs. soybean crop rotation study. When evaluating different crop rotation and residue management systems, soil disturbance may be an important factor affecting the AMF quality and quantity. Therefore, inter- and intra-row samples may need to be collected and looked at to further evaluate the influence of strip-till on AMF communities and subsequent effects on corn colonization, especially if corn is grown after canola.

In our study we looked only at granular forms of fertilizers placed 5 cm beside and 2.5 cm below the seed row. Due to equipment capability and capacity there were no comparisons between in-furrow or deeper side band placements (e.g., 5 cm to the side and 5 cm below the seed). Under many conditions, in-furrow application will remain popular because it is fast, easy and equipment is readily available. Therefore, future studies should consider not only the efficiency of these applications but also the cost, additional application time and equipment modifications required. There were also no comparisons to liquid forms of P. Considering our short season environment and equipment availability, a significant amount of starter fertilizer is applied in furrow as a liquid starter. This would be a valuable comparison with granular fertilizers as different forms may behave differently, influencing nutrient availability. Further, only P was evaluated in both of our studies, and Zn only in the rotation study. Considering different fertilizer analyses can be used for starter fertilizer, inclusion of nutrients such as N, K and micronutrients other than Zn need to be evaluated for corn production in Manitoba.

In both of our studies, starter fertilizer was applied in the spring, where the placement and timing were beneficial for nutrient uptake and crop growth. However, with respect to fall banding we focused on precision placed deep bands (10-13 cm below the soil surface). Corn growers and agronomists in Manitoba may also be interested in investigating fall application of P as shallow precision bands, random deep bands or broadcast applications, since spring operations and field access is often limited due to excess moisture.

In our studies, we used only one hybrid, which responded positively to the application of starter fertilizer. However, a significant amount of research shows that response to starter fertilizer varies with hybrid. Therefore, it is important to assess more hybrids, especially those bred for production in Manitoba. This is of particular interest when selecting short-season vs. long-season hybrids since starter fertilizer may be able to advance maturity, helping the long-season hybrids to realize their yield potential. However, given the variability of response to starter fertilizer among different hybrids, relying on starter fertilizer to advance the maturity of long-season hybrids in our short growing season may be a gamble.

5. REFERENCES

Alloway, B. J. 2004. Zinc in soils and crop nutrition. International Zinc Association and International Fertilizer Industry Association, Brussels, Belgium and Paris, France. [Online] Available: http://www.fertilizer.org/imis20/images/Library_Downloads/2008_IZA_IFA_ZincInSoils.pdf.

An, G. H., Kobayashi, S., Enoki, H., Sonobe, K., Muraki, M., Karasawa, T., and Ezawa, T. 2010. How does arbuscular mycorrhizal colonization vary with host plant genotype? An example based on maize (Zea mays) germplasms. Plant Soil **327**: 441–453. doi:10.1007/s11104-009-0073-3.

Arshad, M. A., and Azooz, R. H. 1996. Tillage effects on soil thermal properties in a semiarid cold region. Soil Sci. Soc. Am. J. **60**: 561–567. doi:10.2136/sssaj1996.03615995006000020032x.

Barry, D. A. J., and Miller, M. H. 1989. Phosphorus nutritional requirement of maize seedlings for maximum yield. Agron. J. **81**: 95–99. doi:10.2134/agronj1989.00021962008100010017x.

Beegle, D. B., Roth, G. W., and Lingenfelter, D. D. 2007. Starter fertilizer. Penn State Extension. Agronomy Facts 51 - UC132.

Bermudez, M., and Mallarino, A. P. 2002. Yield and early growth responses to starter fertilizer in no-till corn assessed with precision agriculture technologies. Agron. J. **94**: 1024–1033. doi:10.2134/agronj2002.1024.

Bermudez, M., and Mallarino, A. P. 2004. Corn response to starter fertilizer and tillage across and within fields having no-till management histories. Agron. J. **96**: 776–785. doi:10.2134/agronj2004.0776.

Biermann, B., and Linderman, R. G. 1981. Quantifying vesicular-arbuscular mycorrhizae: A proposed method towards standardization. New Phytol. **87**: 63–67. doi:10.1111/j.1469-8137.1981.tb01690.x.

Bittman, S., Kowalenko, C. G., Hunt, D. E., Forge, T. A., and Wu, X. 2006. Starter phosphorus and broadcast nutrients on corn with contrasting colonization by mycorrhizae. Agron. J. **98**: 394–401. doi:10.2134/agronj2005.0093.

Bittman, S., Kowalenko, G., and Hunt, D. 2000. Phosphorus deficiency in seedling corn - corn rotation considerations. Better Crop. **84**: 18–20.

Boomsma, C. R., Vyn, T. J., Brewer, J. C., Santini, J. B., and West, T. D. 2006. Corn yield responses to plant height variability resulting from tillage and crop rotation systems in a long-term experiment. Page *in* 17th Triennial Conference of the International Soil Tillage Research Organisation (ISTRO). [Online] Available: http://www.iuss.org/index.php?article_id=149.

Borges, R., and Mallarino, A. P. 2001. Deep banding phosphorus and potassium fertilizers for corn managed with ridge tillage. Soil Sci. Soc. Am. J. **65**: 376–384. doi:10.2136/sssaj2001.652376x.

Brar, N., Lawley, Y., and Tenuta, M. 2016. Does preceding crop affect corn growth and grain yield in Manitoba ? Page *in* Manitoba Agronomist Conference (MAC). Winnipeg, Manitoba.

Brundrett, M. C., Piché, Y., and Peterson, R. L. 1984. A new method for observing the morphology of vesicular-arbuscular mycorrhizae. Botany **62**: 2128–2134. doi:10.1139/b84-290.

Buah, S. S. J., Polito, T. A., and Killorn, R. 1999. No-tillage corn hybrids response to starter fertilizer. J. Prod. Agric. **12**: 676–680.

Bullock, D. G., Simmons, F. W., Chung, I. M., and Johnson, G. I. 1993. Growth analysis of corn grown with or without starter fertilizer. Crop Sci. **33**: 112–117. doi:10.2135/cropsci1993.0011183X003300010021x.

Bundy, L. G., and Andraski, T. W. 1999. Site-specific factors affecting corn response to starter fertilizer. J. Prod. Agric. **12**: 664–670.

Cakmak, I., and Marschner, H. 1987. Mechanism of phosphorus-induced zinc-deficiency in cotton. III. Changes in physiological availability of zinc in plants. Physiol. Plant. **70**: 13–20. doi:10.1111/j.1399-3054.1987.tb08690.x.

Camberato, J., and Maloney, S. 2012. Zinc deficiency in corn. West Lafayette, IN. [Online] Available: https://www.agry.purdue.edu/ext/soilfertility/ZincDeficiencyCorn.pdf.

Campbell, C. R., and Plank, C. O. 2013. Reference sufficiency ranges for plant analysis in the southern region of the United States. [Online] Available: http://www.ncagr.gov/agronomi/saaesd/scsb394.pdf [2017 Apr. 17].

Carsky, R. J., and Reid, W. S. 1990. Response of corn to zinc fertilization. J. Prod. Agric. **3**: 502–506. doi:10.2134/jpa1990.0502.

Carter, M. R., and Gregorich, E. G. 2008. Soil sampling and methods of analysis. 2nd edition. CRC press, Boca Raton, FL.

Cobbina, J., and Miller, M. H. 1987. Purpling in maize hybrids as influenced by temperature and soil phosphorus. Agron. J. **79**: 576. doi:10.2134/agronj1987.00021962007900030035x.

Cromley, S. M., Wiebold, W. J., Scharf, P. C., and Conley, S. P. 2006. Hybrid and planting date effects on corn response to starter fertilizer. Crop Manag.: 1–7. doi:10.1094/CM-2006-0906-01-RS.

Elsokkary, I. H., El-Attar, H. A., and Amer, M. A. 1981. Influence of phosphorus and zinc fertilizers on the uptake of P and Zn by corn plants grown in highly calcareous soils. Plant Soil **59**: 227–236. doi:10.1007/BF02184196.

Evans, D. G., and Miller, M. H. 1990. The role of the external mycelial network in the effect of soil disturbance upon vesicular — arbuscular mycorrhizal colonization of maize. New Phytol. **114**: 65–71.

Faber, B. A., Zasoski, R. J., Burau, R. G., and Uriu, K. 1990. Zinc uptake by corn as affected by vesicular-arbuscular mycorrhizae. Plant Soil **129**: 121–130. doi:10.1007/BF00032404.

Fernández, F. G. 2016. Nutrient management for strip-till and no-till. Page *in* Manitoba Agronomist Conference (MAC). Winnipeg, Manitoba.

Fernández, F. G., and Schaefer, D. 2012. Assessment of soil phosphorus and potassium following real time kinematic-guided broadcast and deep-band placement in strip-till and no-till. Soil Sci. Soc. Am. J. **76**: 1090–1099. doi:10.2136/sssaj2011.0352.

Fernández, F. G., and White, C. 2012. No-till and strip-till corn production with broadcast and subsurface-band phosphorus and potassium. Agron. J. **104**: 996–1005. doi:10.2134/agronj2012.0064.

Galvez, L., Douds, D. D., Drinkwater, L. E., and Wagoner, P. 2001. Effect of tillage and farming system upon VAM fungus populations and mycorrhizas and nutrient uptake of maize. Plant Soil **228**: 299–308. doi:10.1023/A:1004810116854.

Gao, X., Akhter, F., Tenuta, M., Flaten, D. N., Gawalko, E. J., and Grant, C. A. 2010. Mycorrhizal colonization and grain Cd concentration of field-grown durum wheat in response to tillage, preceding crop and phosphorus fertilization. J. Sci. Food Agric. **90**: 750–758. doi:10.1002/jsfa.3878.

Gavito, M. E., and Miller, M. H. 1998a. Changes in mycorrhiza development in maize induced by crop management practices. Plant Soil **198**: 185–192. doi:10.1023/A:1004314406653.

Gavito, M. E., and Miller, M. H. 1998b. Early phosphorus nutrition, mycorrhizae development, dry matter partitioning and yield of maize. Plant Soil **199**: 177–186. doi:10.1023/A:1004357322582.

Gordon, W. B., Fjel, D. L., and Whitney, D. A. 1997. Corn hybrid response to starter fertilizer in a no-tillage , dryland environment. J. Prod. Agric. **10**: 401–404.

Gordon, W. B., and Pierzynski, G. M. 2006. Corn hybrid response to starter fertilizer combinations. J. Plant Nutr. **29**: 1287–1299. doi:10.1080/01904160600767591.

Gordon, W. B., and Whitney, D. A. 1995. No-tillage grain sorghum response to starter nitrogen-phosphorus combinations. J. Prod. Agric. **8**: 369–373.

Grant, C. 2012. Phosphorus management for sensitive crops: Managing phosphorus through the rotation. Page *in* Manitoba Agronomist Conference (MAC). Agriculture and Agri-Food Canada, Winnipeg, Manitoba.

Grant, C., Bittman, S., Montreal, M., Plenchette, C., and Morel, C. 2005. Soil and fertilizer phosphorus: Effects on plant P supply and mycorrhizal development. Can. J. Plant Sci. **85**: 3–14. doi:10.4141/P03-182.

Havlin, J. L., Tisdale, S. L., Nelson, W. L., and Beaton, J. D. 2004. Soil fertility and fertilizers: An introduction to nutrient management. 7th edition. Prentice Hall. [Online] Available: http://www.amazon.com/Soil-Fertility-Fertilizers-Introduction-Management/dp/0130278246.

Heard, J., Grant, C., and Flaten, D. 2014. Phosphorus fertilization strategies for long term agronomic and environmental sustainability. Pages 1–10 *in* Manitoba Agronomist Conference (MAC). Winnipeg, Manitoba. [Online] Available: https://www.gov.mb.ca/agriculture/crops/soil-fertility/pubs/phosphorus-fertilization-strategies-for-manitoba.pdf [2017 Jan. 16].

Hergert, G. W., Wortmann, C. S., Ferguson, R. B., Shapiro, C. A., and Shaver, T. M. 2012. Using starter fertilizers for corn, grain sorghum, and soybeans. NebGuide. [Online] Available: http://extension.unl.edu/publications.

Jokela, W. E. 1992. Effect of starter fertilizer on corn silage yields on medium and high fertility soils. J. Prod. Agric. **5**: 233–237.

Kaiser, D. E., Coulter, J. A., and Vetsch, J. A. 2016. Corn hybrid response to in-furrow starter fertilizer as affected by planting date. Agron. J. **108**: 2493–2501. doi:10.2134/agronj2016.02.0124.

Kaiser, D. E., Lamb, J. A., and Vetsch, J. 2015. Banding fertilizer with the corn seed. [Online] Available: http://www.extension.umn.edu/agriculture/nutrient-management/docs/AGNM-1502-banding-fertilizer-on-the-corn-seed.pdf.

Kaiser, D. E., Mallarino, A. P., and Bermudez, M. 2005. Corn grain yield, early growth, and early nutrient uptake as affected by broadcast and in-furrow starter fertilization. Agron. J. **97**: 620–626. doi:10.2134/agronj2005.0620.

Kim, K.-I., Kaiser, D. E., and Lamb, J. 2013. Corn response to starter fertilizer and broadcast sulfur evaluated using strip trials. Agron. J. **105**: 401–411. doi:10.2134/agronj2012.0299.

Koide, R. T., and Peoples, M. S. 2012. On the nature of temporary yield loss in maize following canola. Plant Soil **360**: 259–269. doi:10.1007/s11104-012-1237-0.

Landry, C. P., Hamel, C., and Vanasse, A. 2008. Influence of arbuscular mycorrhizae on soil P dynamics, corn P-nutrition and growth in a ridge-tilled commercial field. Can. J. Soil Sci. **88**: 283–294. doi:10.4141/CJSS07024.

Lee, J. 2011. Plant Tissue Analysis CSI – From the Field. [Online] Available: http://www.agvise.com/wp-content/uploads/2012/11/2011-John-Plant-Tissue-Seminar.pdf [2017 Apr. 8].

Lu, S., Braunberger, P. G., and Miller, M. H. 1994. Response of vesicular-arbuscular mycorrhizas of maize to various rates of P addition to different rooting zones. Plant Soil **158**: 119–128. doi:10.1007/BF00007924.

Lu, S., and Miller, M. H. 1993. Determination of the most efficient phosphonrs placement for field-grown maize (Zea mays L .) in early growth stages. Can. J. Soil Sci. Sci. **73**: 349–358.

MAFRD 2007. Manitoba Soil Fertility Guide. [Online] Available: https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/pubs/soil_fertility_guide.pdf [2017 Jan. 18].

Mallarino, A. P. 1996. Evaluation of optimum and above-optimum phosphorus supplies by analysis of plant parts. Agron. J. **88**: 376–390. doi:10.2134/agronj1996.00021962008800030003x.

Mallarino, A. P., Bergmann, N., and Kaiser, D. E. 2011. Corn responses to in-furrow phosphorus and potassium starter fertilizer applications. Agron. J. **103**: 685–694. doi:10.2134/agronj2010.0377.

Mallarino, A. P., and Webb, J. R. 1995. Long-term evaluation of phosphorus and zinc interactions in corn. J. Prod. Agric. **8**: 52–55.

Manitoba Corn Growers Association 2014. Corn production in Manitoba. Manitoba Corn Growers Association, Carman. [Online] Available: http://manitobacorn.ca/production/.

Mascagni, H. J., and Boquet, D. J. 1996. Starter fertilizer and planting date effects on corn rotated with cotton. Agron. J. **88**: 975–982. doi:10.2134/agronj1996.00021962003600060022x.

McGonigle, T. P., Evans, D. G., and Miller, M. H. 1990a. Effect of degree of soil disturbance on mycorrhizal colonization and phosphorus absorption by maize in growth chamber and field experiments Effect of degree of soil disturbance on mycorrhizal colonization and phosphorus absorption by maize in growth chamb. New Phytol. **116**: 629–636.

McGonigle, T. P., Hutton, M., Greenley, A., and Karamanos, R. 2011. Role of mycorrhiza in a wheat-flax versus canola-flax rotation: A case study. Commun. Soil Sci. Plant Anal. **42**: 2134–2142. doi:10.1080/00103624.2011.596242.

McGonigle, T. P., and Miller, M. H. 1993. Mycorrhizal development and phosphorus absorption in maize under conventional and reduced tillage. Soil Sci. Soc. Am. J. **57**: 1002–1006. doi:10.2136/sssaj1993.03615995005700040020x.

McGonigle, T. P., Miller, M. H., Evans, D. G., Fairchild, G. L., and Swan, J. A. 1990b. A new method which gives an objective measure of colonization of roots by vesicular-arbuscular mycorrhizal fungi. New Phytol. **115**: 495–501. doi:10.1111/j.1469-8137.1990.tb00476.x.

McGonigle, T. P., Miller, M. H., and Young, D. 1999. Mycorrhizae, crop growth, and crop phosphorus nutrition in maize-soybean rotations given various tillage treatments. Plant Soil **210**: 33–42. doi:10.1023/A:1004633512450.

Mengel, D. B., and Barber, S. A. 1974. Development and distribution of the corn root system under field conditions. Agron. J. **66**: 341–344. doi:10.2134/agronj1974.00021962006600030002x.

Miller, M. H. 2000. Arbuscular mycorrhizae and the phosphorus nutrition of maize: A review of Guelph studies. Can. J. Plant Sci. **80**: 47–52. doi:10.4141/P98-130.

Monreal, M. A., Grant, C. A., Irvine, R. B., Mohr, R. M., McLaren, D. L., and Khakbazan, M. 2011. Crop management effect on arbuscular mycorrhizae and root growth of flax. Can. J. plant Sci. **91**: 315–324. doi:10.4141/CJPS10136.

Niehues, B. J., Lamond, R. E., and Olsen, C. J. 2004. Starter fertilizer management for no-till corn production. Agron. J. **96**: 1412–1418. doi:10.2134/agronj2004.1412.

Nielsen, R. L. 2013. Field drydown of mature corn grain. West Lafayette, IN. [Online] Available: http://www.kingcorn.org/news/timeless/GrainDrying.html%0AField.

Nowatzki, J., Endres, G., Dejong-Hughes, J., and Aakre, D. 2011. Strip till for field crop production. NDSU Extension Service.

O'Halloran, I. P., Miller, M. H., and Arnold, G. 1986. Absorption of P by corn (Zea mays L.) as influenced by soil disturbance. Can. J. Soil Sci. **66**: 287–302.

Osborne, S. L. 2005. Enhancing corn production through the use of starter fertilizer in the Northern Great Plains. Commun. Soil Sci. Plant Anal. **36**: 2421–2429. doi:10.1080/00103620500253340.

Phair, J. 2012. MESZ provided yield response but no economic advantage over MAP. [Online] Available: http://www.todaysfarmer.ca/2012/01/30/mesz-provided-yield-response-but-no-economic-advantage-over-map [2017 Jan. 18].

Randall, G., and Vetsch, J. 2008. Optimum placement of phosphorus for corn/soybean rotations in a strip-tillage system. J. Soil Water Conserv. **63**: 152A–153A. doi:10.2489/jswc.63.5.152A.

Randall, G. W., and Hoeft, R. G. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. J. Prod. Agric. **1**: 70–79. doi:10.2134/jpa1988.0070.

Rehm, G. W., and Lamb, J. 2009. Corn response to fluid fertilizers placed near the seed at planting. Soil Sci. Soc. Am. J. **73**: 1427–1434. doi:10.2136/sssaj2009.0442.

Roth, G. W., Beegle, D. B., Heinbaugh, S. M., and Antle, M. E. 2006. Starter fertilizers for corn on soils testing high in phosphorus in the northeastern USA. Agron. J. **98**: 1121–1127. doi:10.2134/agronj2005.0220.

Scharf, P. C. 1999. On-farm starter fertilizer response in no-till corn. J. Prod. Agric. **12**: 692–695.

Schulte, E. E., and Kelling, K. A. 1991. Plant analysis: a diagnostic tool. [Online] Available: https://www.extension.purdue.edu/extmedia/nch/nch-46.html [2017 Apr. 15].

Schwab, G. J., Whitney, D. A., Kilgore, G. L., and Sweeney, D. W. 2006. Tillage and phosphorus management effects on crop production in soils with phosphorus stratification. Agron. J. **98**: 430–435. doi:10.2134/agronj2005.0050.

Singh, T. A., Thomas, G. W., Moschler, W. W., and Martens, D. C. 1966. Phosphorus uptake by corn (Zea mays L.) under no-tillage and conventional practices. Agron. J. **58**: 147–148. doi:10.2134/agronj1966.00021962005800020006x.

Smith, S. E., Jakobsen, I., Grønlund, M., and Smith, F. A. 2011. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. Plant Physiol. **156**: 1050–1057. doi:10.1104/pp.111.174581.

Soil Classification Working Group 1998. The Canadian system of soil classification. 1646 (Revised), 3rd edition. Agric. and Agri-Food Can. Publ.

Soltangheisi, A., Ishak, C. F., Musa, H. M., Zakikihani, H., and Rahman, Z. A. 2013. Phosphorus and zinc uptake and their interaction effect on dry matter and chlorophyll content of sweet corn (Zea mays var. Saccharata).

Stammer, A. J. 2015. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean in Iowa. Iowa State University.

Statistics Canada 2016. Principal field crop areas. The Daily. doi:11-001-X.

Stewart, G. 2012. Including zinc and sulphur in starter fertilizer blends for corn: 2012 summary. Crop Advances: Field Crop Reports. Guelph, ON.

Stukenholtz, D. D., Olsen, R. J., Gogan, G., and Olson, R. A. 1966. On the mechanism of phosphorus-zinc interaction in corn nutrition. Soil Sci. Soc. Am. J. **30**: 759–763. doi:10.2136/sssaj1966.03615995003000060029x.

Sutradhar, A. K., Kaiser, D. E., Rosen, C. J., and Lamb, J. A. 2016. Zinc for crop production. Nutrient Management.

Swan, J. B., Higgs, R. L., Bailey, T. B., Wollenhaupt, N. C., Paulson, W. H., and Peterson, A. E. 1994. Surface residue and in-row treatment effects on long-term no-tillage continuous corn. Agron. J. **86**: 711–718. doi:10.2134/agronj1994.00021962008600040024x.

Teare, I. D., and Wright, D. L. 1990. Corn hybrid-starter fertilizer interaction for yield and lodging. Crop Sci. **30**: 1298–1303. doi:10.2135/cropsci1990.0011183X003000060028x.

Vetsch, J. A., and Randall, G. W. 2002. Corn production as affected by tillage system and starter fertilizer. Agron. J. **94**: 532–540. doi:10.2134/agronj2002.0532.

Vyn, T. J. 2008. 2008 Illinois Crop Protection Technology Conference. Pages 70–75 *in* Tillage and fertility placement aspects of root zone optimization for corn.

Vyn, T. J., and Raimbault, B. A. 1992. Evaluation of strip tillage systems for corn production in Ontario. Soil Tillage Res. **23**: 163–176. doi:10.1016/0167-1987(92)90012-Z.

Wiatrak, P. J., Wright, D. L., and Marois, J. J. 2007. Comparing the growth, weed control, and yields of cotton on two tillage systems in the Southeast. Crop Manag. **6**: 1–6. doi:10.1094/CM-2007-0815-01-RS.Abstract.

Wolkowski, R. P. 2000. Row-placed fertilizer for maize grown with an in-row crop residue management system in southern Wisconsin. Soil Tillage Res. **54**: 55–62. doi:10.1016/S0167-1987(99)00114-2.

Wortmann, C. S., Xerinda, S. A., Mamo, M., and Shapiro, C. A. 2006. No-till row crop response to starter fertilizer in Eastern Nebraska: I. Irrigated and rainfed corn. Agron. J. **98**: 156–162. doi:10.2134/agronj2005.0015.

6. APPENDICES

Appendix A

Materials and Methods (Chapter 2)

Appendix A.1 Summary of preceding crop treatment (canola, soybean) varieties, planting and harvest date and average yield (Chapter 2)

Site-Year	Crop	Planting Date	Harvest Date	Variety	Average Yield
					— $kg\ ha^{-1}$ —
Carman 2015	Canola	-[a]	-[a]	DEKALB 73-75 RR	1298[b]
	Soybean	-[a]	2014 Oct. 08	DEKALB 24-10 RY RR	2218
Stephenfield 2015	Canola	2014 May 29	2014 Oct. 09	Liberty 150	745
	Soybean	2014 May 29	2014 Oct. 09	DEKALB 24-10 RY RR	1602
Carman 2016	Canola	2015 May 21	2015 Sep. 02	InVigor L252	1167
	Soybean	2015 May 21	2015 Sep. 28	DEKALB 24-10 RY RR	3426

[a] Crops were planted and harvested by the Plant Science Department, University of Manitoba.
[b] Estimated canola yield based on Carman station averages for 2014, samples were lost.

Appendix A.2 Basal rates of K, S, Zn and Cu applied at each site-year in 2015 and 2016 (Chapter 2)

Site-year	Nutrients Applied			
	K	S	Zn	Cu
	kg ha^{-1}			
Carman 2015	67[a]	-	-[b]	-
Stephenfield 2015	167[c]	15[d]	-[b]	0.125[e]
Carman 2016	-	28[f]	-[b]	-

[a] 67 kg K_2O ha^{-1} broadcasted and incorporated on 2014 Oct.21 as potash (0-0-60).
[b] Zinc was not applied since the fertilizer treatments included Zn.
[c] 123 kg K_2O ha^{-1} broadcasted and incorporated on 2014 Oct.29 as potash (0-0-60), additional 44 kg K_2O ha^{-1} broadcasted on 2015 June 29 as potassium sulphate (0-0-50-17).
[d] Sulphur broadcasted on 2015 June 29 as potassium sulphate (0-0-50-17), rates were adjusted for S in the fertilizer treatments.
[e] Foliar copper applied as copper chelate (14% Cu) on 2015 July 06, rates were adjusted for a canopy factor and only half of recommended rate was applied.
[f] Sulphur broadcasted on 2016 May 12 as ammonium sulphate (21-0-0-24) and incorporated with the corn planter.

Appendix A.3 Dates for early season, mid to late season and late season crop measurements and soil measurements Carman 2015, Stephenfield 2015 and Carman 2016 (Chapter 2)

		Site-year		
Time of season	Crop Measurement	Carman 2015	Stephenfield 2015	Carman 2016
		Sampling Date		
Early Season	Plant counts (2 wk)	June 08	June 09	May 26
	Plant counts (4 wk)	June 24	June 24	June 08
	Roots collected (AMF)	June 26	June 25	June 20
	Early season biomass	June 26	June 25	June 20
	Green seeker NDVI	July 08	July 13	June 27
	Plant height	July 08	July 13	July 08
Mid to Late Season	Maturity assessment	July 27	July 27	July 25
	In-season cob moisture[a]	Sep. 01	Sep. 01	Aug. 16
		Sep. 12	Sep. 12	Aug. 23
		Sep. 21	Sep. 21	Sep. 01
		Sep. 28	Sep. 28	Sep. 08
		Oct. 05	Oct. 05	Sep. 13
		Oct. 10		Sep. 20
				Sep. 28
Late Season	Moisture (harvest)	Oct. 15	Oct. 14	Oct. 05
	Yield (harvest)	Oct. 15	Oct. 14	Oct. 05
	Test Weight (harvest)	Oct. 15	Oct. 14	Oct. 05
	Soil Measurements			
	Giddings (spring)	May 01	May 01	May 04
	Giddings (fall)	Oct. 22	Oct. 22	Oct. 19
	Temperature iButtons (in)	May 27	May 27	May 12
	Temperature iButtons (out)	Oct. 15	Oct. 15	June 14

[a] Frequency of in-season cob moisture measurements varied between site-years due to limited availability of the Electrophysics® moisture meter in 2015.

Appendix A.4 Corn crop herbicide application dates, products and rates for at Carman and Stephenfield in 2015 and Carman in 2016 (Chapter 2)

Site-year	Herbicide Application		
	Date of Application	Product	Rate
			—L ha^{-1}—
Carman 2015	2015 June 11	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
	2015 June 29 – July 02	Mechanical weed control	-
	2015 July 20	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
		Logic M (225 g/L bromoxynil and 225 g/L of MCPA ester formulated as an emulsifiable concentrate)	0.5
Stephenfield 2015	2015 May 19[a]	*Heat WG* (70 % saflufenacil formulated as a water soluble granule)	52[b]
		Credit (356 g a.e./L glyphosate formulated as a solution)	2.5
		Merge adjuvant	0.5
	2015 June 11[c]	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
	2015 June 26	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.2
	2015 July 02	*Logic M* (225 g/L bromoxynil and 225 g/L of MCPA ester formulated as an emulsifiable concentrate)	1.1
Carman 2016	2016 May 09[a]	*Heat WG* (70 % saflufenacil formulated as a water soluble granule)	52[b]
		Roundup WeatherMax (540 g a.e./L glyphosate formulated as a solution)	1.67
		Merge adjuvant	0.5
	2016 June 07	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	1.65
	2016 July 08	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	1.0
		Bromotril II (240 g/L bromoxynil formulated as an emulsifiable concentrate	1.4

[a] Pre-plant burn-off application.
[b] Granules measured in g ha^{-1}.
[c] Application to the surrounding border area of the study site only, no herbicide application in the study plots.

Appendix A.5 Canola and soybean crop herbicide application dates, products and rates for at Carman and Stephenfield in 2015 and Carman in 2016 (Chapter 2)

Site-year	Herbicide Application			
	Crop	Date of Application	Product	Rate
				— L ha^{-1}—
Carman 2014	Canola	2014 July 25[a]	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	0.82
	Soybean	2014 July 25[a]	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	0.82
Stephenfield 2014		2014 May 26[b]	*Heat WG* (70 % saflufenacil formulated as a water soluble granule)	25.7[c]
			Roundup WeatherMax (540 g a.e./L glyphosate formulated as a solution)	1.67
			Merge adjuvant	0.5
	Canola	2014 July 02	*Liberty 150SN* (150 g/L glufosinate ammonium formulated as a solution)	2.72
	Soybean	2014 July 03	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.74
Carman 2015	Canola	2014 June 18	*Liberty 150SN* (150 g/L glufosinate ammonium formulated as a solution)	2.72
	Soybean	2014 June 18	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.74

[a] Sprayed by Department of Plant Science, University of Manitoba.
[b] Pre-plant burn-off application.
[c] Granules measured in g ha^{-1}.

Appendix B

Early Season Measurements (Chapter 2)

Appendix B.1a Plant stands at two weeks after planting at Carman 2015, Stephenfield 2015 and Carman 2016 (Chapter 2)

Treatment						Site-year[a]		
Preceding Crop	Fertilizer Treatment			Products[b]		Carman	Stephenfield	Carman
	P_2O_5	S	Zn			2015	2015	2016
	kg ha^{-1}					plants ha^{-1}		
Canola	0	0	0	Control (no starter)		67434	70313	72369*a*[c]
	30	7.5	0	MAP + AS		69079	76069	69901*ab*
	60	15	0	MAP + AS		73191	76891	60444*b*
	30	7.5	0.75	MESZn		71957	79770	68668*ab*
	60	15	1.5	MESZn		71135	78947	70724*ab*
Soybean	0	0	0	Control (no starter)		69902	75658	66201*ab*
	30	7.5	0	MAP + AS		66201	75658	64556*ab*
	60	15	0	MAP + AS		68257	76069	71546*ab*
	30	7.5	0.75	MESZn		69490	75658	67434*ab*
	60	15	1.5	MESZn		64556	74013	68257*ab*
Canola						70559	76398	68421
Soybean						67681	75411	67599
	0	0	0	Control (no starter)		68668	72985	69285
	30	7.5	0	MAP + AS		67640	75864	67229
	60	15	0	MAP + AS		70724	76480	65995
	30	7.5	0.75	MESZn		70724	77714	68051
	60	15	1.5	MESZn		67846	76480	69490
						68668	72985	69285
ANOVA					Df		Pr>F	
Fert					4	0.4538	0.3881	0.5443
Crop					1	0.2069	0.5226	0.5803
Crop*Fert					4	0.3339	0.2532	0.0058
Coeff Var (C.V.)						7	7	8

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix B.1b Plant stands at four weeks after planting at Carman 2015, Stephenfield 2015 and Carman 2016 (Chapter 2)

Treatment						Site-year[a]		
Preceding Crop	Fertilizer Treatment			Products[b]		Carman	Stephenfield	Carman
	P_2O_5	S	Zn			2015	2015	2016
		kg ha^{-1}					plants ha^{-1}	
Canola	0	0	0	Control (no starter)		65789	71546	79770
	30	7.5	0	MAP + AS		67434	78536	78536
	60	15	0	MAP + AS		74424	77714	77714
	30	7.5	0.75	MESZn		74013	78536	81003
	60	15	1.5	MESZn		69901	79770	80181
Soybean	0	0	0	Control (no starter))		67846	77303	81003
	30	7.5	0	MAP + AS		67434	75247	81004
	60	15	0	MAP + AS		66612	79358	81003
	30	7.5	0.75	MESZn		68257	74425	80181
	60	15	1.5	MESZn		62911	77303	78125
Canola						70312	77220	79441
Soybean						66612	76727	80263
	0	0	0	Control (no starter)		66817	74424	80387
	30	7.5	0	MAP + AS		67434	76892	79770
	60	15	0	MAP + AS		70518	78536	79359
	30	7.5	0.75	MESZn		71135	76480	80592
	60	15	1.5	MESZn		66406	78536	79153
						66817	74424	80387
ANOVA					Df		Pr>F	
Fert					4	0.2162	0.3636	0.7891
Crop					1	0.0782	0.7636	0.3466
Crop*Fert					4	0.2091	0.1897	0.2749
Coeff Var (C.V.)						8	6	3

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn)

Appendix B.2 Symptoms of phosphorus deficiency as a purpling colouration due to anthocyanin production in young corn leaves at V3 stage, corn after canola, at Carman in 2015.

Appendix B.3a Hyphal colonization of corn roots at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				%			
Canola	0	0	0	Control (no starter)	19	13	8	13
	60	15	1.5	MESZn	16	14	8	13
Soybean	0	0	0	Control (no starter)	17	20	10	16
	60	15	1.5	MESZn	14	19	18	17
Canola					17	13	8	13
Soybean					15	19	14	16
	0	0	0	Control (no starter)	18	16	9	14
	60	15	1.5	MESZn	15	16	13	15
Site-year					16*A*[c]	16*A*	11*B*	

ANOVA	Df	Pr>F
Fert	1	0.7713
Crop	1	0.0643
Crop*Fert	1	0.3876
Site-year	2	0.0244*
Site-year*Fert	2	0.0545
Site-year*Crop	2	0.1108
Site-year*Crop*Fert	2	0.1061
Coeff Var (C.V.)		42

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix B.3b Vesicular colonization of corn roots at V4: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				%			
Canola	0	0	0	Control (no starter)	5	3	7	5
	60	15	1.5	MESZn	3	5	3	4
Soybean	0	0	0	Control (no starter)	2	4	8	5
	60	15	1.5	MESZn	4	4	8	5
Canola					4	4	5	4
Soybean					3	4	8	5
	0	0	0	Control (no starter)	3	4	7	5
	60	15	1.5	MESZn	3	4	5	4
Site-year					3*B*[c]	4*AB*	6*A*	

ANOVA	Df	Pr>F
Fert	1	0.3381
Crop	1	0.4416
Crop*Fert	1	0.2059
Site-year	2	0.0376*
Site-year*Fert	2	0.1016
Site-year*Crop	2	0.2063
Site-year*Crop*Fert	2	0.0935
Coeff Var (C.V.)		67

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix B.4a Differences in corn root size in unfertilized control plots, corn after canola (a) and corn after soybean (b) at Carman in 2015 (Chapter 2).

Appendix B.4b Differences in corn root size in unfertilized control plots, corn after canola (a) and corn after soybean (b) at Stephenfield in 2015 (Chapter 2).

Appendix B.5 Normalized Difference Vegetation Index

Corn normalized difference vegetation index (NDVI) was assessed using a GreenSeeker® handheld crop sensor at V7 growth stage in 2015 and at V5 growth stage in 2016. Two passes were made on the two middle rows for the entire plot length and an average of the readings was recorded to represent plant biomass density. In 2015, NDVI differences between fertilizer treatments and the unfertilized control were significant but smaller compared to differences observed in 2016 since the canopy has already closed up at the V7 stage. In 2016, NDVI measurements were taken at an earlier stage of corn development in order to capture larger plant biomass density differences. Since NDVI measurements were taken at two different stages of development, 2015-2016 site-years cannot be combined for statistical analysis.

Appendix B.5, continued Normalized Difference Vegetation Index: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]				
Preceding Crop	Fertilizer Treatment			Products[b]	Carman[c]	Stephenfield[c]	Carman[d]	All sites	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015	2016
	kg ha^{-1}				NDVI				
Canola	0	0	0	Control (no starter)	0.72	0.71	0.31	0.71	-[e]
	30	7.5	0	MAP + AS	0.73	0.72	0.46	0.72	-[e]
	60	15	0	MAP + AS	0.74	0.72	0.51	0.73	-[e]
	30	7.5	0.75	MESZn	0.73	0.71	0.49	0.72	-[e]
	60	15	1.5	MESZn	0.73	0.71	0.54	0.72	-[e]
Soybean	0	0	0	Control (no starter)	0.73	0.71	0.40	0.72	-[e]
	30	7.5	0	MAP + AS	0.74	0.73	0.50	0.73	-[e]
	60	15	0	MAP + AS	0.73	0.73	0.52	0.73	-[e]
	30	7.5	0.75	MESZn	0.73	0.73	0.49	0.73	-[e]
	60	15	1.5	MESZn	0.74	0.72	0.51	0.73	-[e]
Canola					0.73	0.71	0.46	0.72	-[e]
Soybean					0.73	0.72	0.48	0.73	-[e]
	0	0	0	Control (no starter)	0.72	0.71	0.35*b*[f]	0.71*b*	-[e]
	30	7.5	0	MAP + AS	0.73	0.72	0.48*a*	0.73*a*	-[e]
	60	15	0	MAP + AS	0.74	0.72	0.51*a*	0.73*a*	-[e]
	30	7.5	0.75	MESZn	0.73	0.72	0.49*a*	0.73*a*	-[e]
	60	15	1.5	MESZn	0.73	0.71	0.53*a*	0.72*a*	-[e]
Site-year					0.73*A*[f]	0.72*B*	-[e]		

ANOVA	Df	Pr>F		
Fert	4	<.0001*		
Crop	1	0.1042		
Crop*Fert	4	0.0892		
Coeff Var (C.V.)		16		
Fert	4		0.0014*	-[e]
Crop	1		0.1661	-[e]
Crop*Fert	4		0.7825	-[e]
Site-year	1		0.0235*	-[e]
Site-year*Fert	4		0.7323	-[e]
Site-year*Crop	1		0.6745	-[e]
Site-year*Crop*Fert	4		0.2449	-[e]
Coeff Var (C.V.)			2	

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); Microessentials SZ (MESZn, 12-40-0-10-1Zn).
[c] NDVI values recorded at V7 corn stage.
[d] NDVI values recorded at V5 corn stage.
[e] Only data from one site-year (Carman 2016) was analyzed for 2016 season, no combined data for this year.
[f] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping; A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix C

Mid to Late Season Crop Measurements (Chapter 2)

Appendix C.1a. Days to 50% pollen shed

The number of days from planting until the day when ≥50% of the plants in the two centre rows of each plot had reached 50% pollen shed was recorded for each plot. Days to 50% pollen shed were assessed following full tassel emergence. In 2015, the maturity ratings assigned in the field suggest that 50% pollen shed occurred prior to silking. However, pollen shed normally begins 2-3 d after complete tassel emergence from the whorl and silks are pollinated within 4-10 d after tassel emergence (Manitoba Corn Growers Association 2014). Therefore, if pollen shed occurred after the silks developed it would have caused synchronous pollen well, drying out the silks. However, silks did not dry out and fertilization occurred, indicating that days to 50% pollen shed may not have been the most accurate estimate of crop maturity in 2015, and rather days to silking can be a better predictor of corn developmental stage.

Appendix C.1a, continued Days to 50% pollen shed: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				DAP[c]			
Canola	0	0	0	Control (no starter)	65.2*Ba*[d]	63.5*Ca*	77.5*Aa*	68.5
	30	7.5	0	MAP + AS	63.3*Bb*	63.0*Ba*	71.2*Ac*	65.7
	60	15	0	MAP + AS	64.0*Bb*	63.0*Ca*	71.0*Ac*	65.9
	30	7.5	0.75	MESZn	64.0*Bb*	63.0*Ca*	70.7*Ac*	65.8
	60	15	1.5	MESZn	64.0*Bb*	63.0*Ca*	71.0*Ac*	65.9
Soybean	0	0	0	Control (no starter)	63.8*Bb*	63.5*Ba*	73.0*Ab*	66.6
	30	7.5	0	MAP + AS	63.5*Bb*	63.0*Ba*	71.0*Ac*	65.7
	60	15	0	MAP + AS	63.5*Bb*	63.2*Ba*	71.0*Ac*	65.8
	30	7.5	0.75	MESZn	63.5*Bb*	63.0*Ba*	71.5*Ac*	65.9
	60	15	1.5	MESZn	64.0*Bb*	63.0*Ca*	71.0*Ac*	65.9
Canola					64.1	63.1	72.3	66.4
Soybean					63.6	63.1	71.5	66.0
	0	0	0	Control (no starter)	64.5	63.5	75.2	67.5
	30	7.5	0	MAP + AS	63.4	63.0	71.1	65.7
	60	15	0	MAP + AS	63.7	63.1	71.0	65.9
	30	7.5	0.75	MESZn	63.7	63.0	71.1	65.9
	60	15	1.5	MESZn	64.0	63.0	71.0	65.9
Site-year					63.9	63.1	71.9	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.0043*
Crop*Fert	4	<.0001*
Site-year	2	<.0001*
Site-year*Fert	8	<.0001*
Site-year*Crop	2	0.0319*
Site-year*Crop*Fert	8	<.0001*
Coeff Var (C.V.)		6

[a] Geometric means presented from Proc Glimmix using *ilink* back-transformation; Original data transformed using gamma distribution.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] DAP, days after planting.
[d] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Figure C.1b Visual differences in maturity and tasseling on 2016 July 20 at Carman (L) 30 kg P_2O_5 ha^{-1} spring side banded MAP (M) unfertilized control (R) 30 kg P_2O_5 ha^{-1} spring side band MESZn, corn on canola stubble.

Appendix C.2a Late season cob moisture recorded from R4 until harvest at Carman 2015: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Dates[a]					
Preceding Crop	Fertilizer Treatment			Products[b]	Sep. 01	Sep. 12	Sep. 21	Sep. 28	Oct. 05	Oct. 10
	P_2O_5	S	Zn							
	kg ha^{-1}				g kg^{-1}					
Canola	0	0	0	Control (no starter)	51	43	36	31	30	26
	30	7.5	0	MAP + AS	50	39	34	30	27	24
	60	15	0	MAP + AS	50	39	34	28	28	22
	30	7.5	0.75	MESZn	50	39	35	27	28	23
	60	15	1.5	MESZn	51	39	33	27	29	23
Soybean	0	0	0	Control (no starter)	52	44	37	31	31	25
	30	7.5	0	MAP + AS	51	41	35	30	29	24
	60	15	0	MAP + AS	52	42	35	30	30	23
	30	7.5	0.75	MESZn	51	42	34	28	29	25
	60	15	1.5	MESZn	52	44	36	30	30	25
Canola					50	40	34	28	28	24
Soybean					51	42	35	30	30	24
	0	0	0	Control (no starter)	51	43	36	31	30	26
	30	7.5	0	MAP + AS	50	40	35	30	28	24
	60	15	0	MAP + AS	51	40	34	29	29	23
	30	7.5	0.75	MESZn	51	40	34	28	28	24
	60	15	1.5	MESZn	51	41	35	29	29	24
Day					51*A*[c]	41*B*	35*C*	29*D*	29*D*	24*E*

ANOVA	Df	Pr>F
Day	5	<.0001*
Day*Crop	5	0.1177
Day*Fert	20	0.6057
Day*Crop*Fert	20	0.9720
Coeff Var (C.V.)		27

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-E Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Appendix C.2b Late season cob moisture recorded from R4 until harvest at Stephenfield 2015: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Dates[a]				
Preceding Crop	Fertilizer Treatment			Products[b]	Sep. 01	Sep. 12	Sep. 21	Sep. 28	Oct. 05
	P_2O_5	S	Zn						
	kg ha^{-1}				g kg^{-1}				
Canola	0	0	0	Control (no starter)	52	45	34	29	25
	30	7.5	0	MAP + AS	52	43	30	27	21
	60	15	0	MAP + AS	50	41	31	26	21
	30	7.5	0.75	MESZn	51	42	29	29	22
	60	15	1.5	MESZn	51	39	28	24	20
Soybean	0	0	0	Control (no starter)	50	45	31	28	22
	30	7.5	0	MAP + AS	51	46	31	29	23
	60	15	0	MAP + AS	51	43	31	26	22
	30	7.5	0.75	MESZn	51	44	31	29	23
	60	15	1.5	MESZn	51	42	32	25	21
Canola					51	42	30	27	22
Soybean					51	44	31	27	22
	0	0	0	Control (no starter)	51*Aa*[c]	45*Ba*	33*Ca*	28*Dab*	24*Ea*
	30	7.5	0	MAP + AS	51*Aa*	45*Ba*	30*Cab*	28*Cab*	22*Dab*
	60	15	0	MAP + AS	51*Aa*	42*Bb*	31*Cab*	26*Dbc*	22*Eab*
	30	7.5	0.75	MESZn	51*Aa*	43*Bab*	30*Cb*	29*Ca*	23*Dab*
	60	15	1.5	MESZn	51*Aa*	40*Bb*	30*Cab*	25*Cc*	20*Eb*
Day					51	43	31	27	22

ANOVA	Df	Pr>F
Day	4	<.0001*
Day*Crop	4	0.1193
Day*Fert	16	0.0064*
Day*Crop*Fert	16	0.7911
Coeff Var (C.V.)		31

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-E Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix C.2c Late season cob moisture recorded from R4 until harvest at Carman 2016: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Dates[a]						
Preceding Crop	Fertilizer Treatment			Products[b]	Aug. 16	Aug. 23	Sep. 01	Sep. 08	Sep. 13	Sep. 20	Sep. 28
	P_2O_5	S	Zn								
	kg ha^{-1}				g kg^{-1}						
Canola	0	0	0	Control (no starter)	63	45	50	57	36	43	53
	30	7.5	0	MAP + AS	60	41	42	53	59	39	49
	60	15	0	MAP + AS	56	59	36	48	57	35	41
	30	7.5	0.75	MESZn	54	58	36	42	54	69	37
	60	15	1.5	MESZn	48	53	58	38	48	57	35
Soybean	0	0	0	Control (no starter)	60	43	49	57	34	41	52
	30	7.5	0	MAP + AS	59	37	41	53	59	35	49
	60	15	0	MAP + AS	55	59	37	48	57	36	40
	30	7.5	0.75	MESZn	52	58	35	41	54	59	37
	60	15	1.5	MESZn	47	53	59	36	50	57	34
Canola					62	58	54	50	43	39	37
Soybean					59	57	53	49	42	38	35
	0	0	0	Control (no starter)	61	59	55	53	47	44	39
	30	7.5	0	MAP + AS	59	58	53	49	41	37	35
	60	15	0	MAP + AS	59	57	53	48	41	37	35
	30	7.5	0.75	MESZn	59	57	54	49	42	37	35
	60	15	1.5	MESZn	64	57	52	49	41	37	35
Day					60*A*[c]	57*B*	53*C*	50*D*	42*E*	38*F*	36*G*

ANOVA	Df	Pr>F
Day	6	<.0001*
Day*Crop	6	0.6425
Day*Fert	24	0.0571
Day*Crop*Fert	24	0.7013
Coeff Var (C.V.)		20

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] A-G Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Appendix D

Late Season Crop Measurements (Chapter 2)

Appendix D.1 Test weight at harvest: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band

Treatment					Site-year[a]			
Preceding Crop	Fertilizer Treatment			Products[b]	Carman	Stephenfield	Carman	All sites
	P_2O_5	S	Zn		2015	2015	2016	2015-2016
	kg ha^{-1}				g 0.5 L^{-1}			
Canola	0	0	0	Control (no starter)	341	340	313	331*c*[c]
	30	7.5	0	MAP + AS	354	349	320	341*ab*
	60	15	0	MAP + AS	352	351	322	342*a*
	30	7.5	0.75	MESZn	354	350	321	342*a*
	60	15	1.5	MESZn	355	353	323	344*a*
Soybean	0	0	0	Control (no starter)	342	342	320	335*bc*
	30	7.5	0	MAP + AS	351	346	324	340*ab*
	60	15	0	MAP + AS	350	349	323	341*ab*
	30	7.5	0.75	MESZn	349	348	323	340*ab*
	60	15	1.5	MESZn	346	353	325	341*a*
Canola					351	349	320	340
Soybean					347	348	323	339
	0	0	0	Control (no starter)	342	341	316	333
	30	7.5	0	MAP + AS	352	348	322	341
	60	15	0	MAP + AS	351	350	322	341
	30	7.5	0.75	MESZn	351	349	322	341
	60	15	1.5	MESZn	350	353	324	342
Site-year					349A[c]	348A	321B	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.7078
Crop*Fert	4	0.0440*
Site-year	2	<.0001*
Site-year*Fert	8	0.1833
Site-year*Crop	2	0.2331
Site-year*Crop*Fert	8	0.7513
Coeff Var (C.V.)		4

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping. A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping;
[*] Significant at $P< 0.05$.

Appendix E

Materials and Methods (Chapter 3)

Appendix E.1 Basal rates of K, S, Zn and Cu applied at each site-year in 2015 and 2016 (Chapter 3)

Site-year	Nutrients Applied			
	K	S	Zn	Cu
	kg ha^{-1}			
Carman 2015	84[a]	22[b]	0.34[c]	-
Portage la Prairie 2015	-	-	-	-
Carman 2016	50[d]	22[e]	-	-
Portage la Prairie 2016	-	-	-	-

[a] 50 kg K_2O ha^{-1} deep banded 10-13 cm deep with the strip-till unit on 2014 Oct.20 as potash (0-0-60), additional 34 kg K_2O ha^{-1} side-banded with the corn planter at planting on 2015 May 25 as potash (0-0-60).
[b] Sulphur broadcasted on 2015 May 25 as ammonium sulphate (21-0-0-24) and incorporated with the corn planter.
[c] Foliar zinc applied as zinc sulphate (36% Zn) on 2015 July 08.
[d] 50 kg K_2O ha^{-1} deep banded 10-13 cm deep with the strip-till unit on 2015 Oct.21 as potash (0-0-60).
[e] Sulphur broadcasted on 2016 May 12 as ammonium sulphate (21-0-0-24) and incorporated with the corn planter.

Appendix E.2 Dates for early season, mid to late season and late season crop measurements and soil measurements Carman 2015, 2016 and Portage la Prairie 2015, 2016 (Chapter 3)

Time of season	Crop Measurement	Site-year			
		Carman 2015	Portage 2015	Carman 2016	Portage 2016
		Sampling Date			
Early Season	Plant counts (2 wk)	June 08	June 09	May 26	May 30
	Plant counts (4 wk)	June 24	June 25	June 08	June 13
	Early season biomass	June 26	June 25	June 20	June 21
	Green seeker NDVI	July 08	July 09	June 27	June 28
	Plant height	July 08	July 09	July 08	July 06
Mid to Late Season	Maturity assessment	July 27	July 31	July 25	July 26
	In-season cob moisture[a]	Sep. 01	Sep. 03	Aug. 16	Aug. 16
		Sep. 12	Sep. 21	Aug. 23	Aug. 23
		Sep. 21	Sep. 28	Sep. 01	Aug. 31
		Sep. 28	Oct. 05	Sep. 08	Sep. 07
		Oct. 05	Oct. 13	Sep. 13	Sep. 14
		Oct. 10		Sep. 20	Sep. 21
				Sep. 28	Sep. 28
Late Season	Moisture (harvest)	Oct. 16	Oct. 19	Oct. 05	Oct. 06
	Yield (harvest)	Oct. 16	Oct. 19	Oct. 05	Oct. 06
	Test Weight (harvest)	Oct. 16	Oct. 19	Oct. 05	Oct. 06
	Soil Measurements				
	PRS probes (in)	June 01	June 03	May 26	May 30
	PRS probes (out)	June 15	June 17	June 08	June 13
	Giddings (spring)	May 01	June 09	May 04	May 17
	Giddings (fall)	Oct. 22	Nov. 13	Oct.19	Oct. 25
	Temperature iButtons (in)	May 27	May 27	May 12	May 16
	Temperature iButtons (out)	Oct. 16	Oct. 19	June 14	June 20
	Residue Assessment	June 08	June 09	May 30	May 30

[a] Frequency of in-season cob moisture measurements varied between site-years due to limited availability of the Electrophysics® moisture meter in 2015.

Appendix E.3 Corn crop herbicide application dates, products and rates for at Carman 2015, 2016 and Portage la Prairie 2015, 2016 (Chapter 3)

Site-year	Herbicide Application		
	Date of Application	Product	Rate
			— L ha^{-1} —
Carman 2015	2015 June 04	*Credit* (356 g a.e./L glyphosate formulated as a solution)	0.6
	2015 June 16	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
	2015 July 06	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
		Logic M (225 g/L bromoxynil and 225 g/L of MCPA ester formulated as an emulsifiable concentrate)	0.5
Portage la Prairie 2015	2015 June 04	*Credit* (356 g a.e./L glyphosate formulated as a solution)	0.6
	2015 June 16	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
	2015 July 14	*Credit* (356 g a.e./L glyphosate formulated as a solution)	1.5
		Logic M (225 g/L bromoxynil and 225 g/L of MCPA ester formulated as an emulsifiable concentrate)	0.5
Carman 2016	2016 May 09[a]	*Heat WG* (70 % saflufenacil formulated as a water soluble granule)	52[b]
		Roundup WeatherMax (540 g a.e./L glyphosate formulated as a solution)	1.67
		Merge adjuvant	0.5
	2016 June 07	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	1.65
	2016 July 08	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	1.0
		Bromotril II (240 g/L bromoxynil formulated as an emulsifiable concentrate	1.4
Portage la Prairie 2016	2016 May 17[a]	*Heat WG* (70 % saflufenacil formulated as a water soluble granule)	52[b]
		Roundup WeatherMax (540 g a.e./L glyphosate formulated as a solution)	1.67
		Merge adjuvant	0.5
	2016 June 07	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	1.65
	2016 July 06	*Roundup WeatherMax* (540 g a.e./L glyphosate formulated as a solution)	1.5

[a] Pre-plant burn-off application.
[b] Granules measured in g ha^{-1}.

Appendix F

Early Season Measurements (Chapter 3)

Appendix F.1a Plant stands at two weeks after planting at Carman 2015, 2016 and Portage la Prairie 2015, 2016 (Chapter 3)

Treatment				Site-year[a]			
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage
	P_2O_5			2015	2015	2016	2016
	kg ha^{-1}			plants ha^{-1}			
Conventional	0	Control (no P)		58800	70724	59622	69490*ab*[e]
	30	Spring	SB	62911	71135	65378	68219*b*
	60	Spring	SB	51398	72369	61678	66127*b*
	30	Fall	DB	64897	72780	51809	77714*ab*
	60	Fall	DB	61678	74013	62500	76892*ab*
Strip-till	0	Control (no P)		69079	67434	66201	78536*ab*
	30	Spring	SB	66153	74424	71135	81003*a*
	60	Spring	SB	60033	72369	66201	77714*ab*
	30	Fall	DB	48235	67434	70724	73602*ab*
	60	Fall	DB	56743	70724	76069	76480*ab*
Conventional				59937	72204	60197*b*	71688
Strip-till				60048	70477	70066*a*	77467
	0	Control (no P)		63939	69079	62911	74013
	30	Spring	SB	64532	72780	68257	74611
	60	Spring	SB	55716	72369	63939	71920
	30	Fall	DB	56566	70107	61266	75658
	60	Fall	DB	59211	72368	69285	76686
ANOVA			Df	Pr>F			
Fert			4	0.5868	0.5511	0.0516	0.5099
Tillage			1	0.9820	0.3101	0.0117*	0.0020*
Crop*Tillage			4	0.3718	0.5201	0.1042	0.0103*
Coeff Var (C.V.)				21	7	13	9

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Appendix F.1b Plant stands at four weeks after planting at Carman 2015, 2016 and Portage la Prairie 2015, 2016 (Chapter 3)

Treatment					Site-year[a]			
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]		Carman	Portage	Carman	Portage
	P_2O_5				2015	2015	2016	2016
	kg ha^{-1}				plants ha^{-1}			
Conventional	0	Control (no P)			68257	73191	81415	81826*a*[e]
	30	Spring	SB		69079	74835	81004	82237*a*
	60	Spring	SB		60033	73602	76480	82785*a*
	30	Fall	DB		68023	76891	77303	85526*a*
	60	Fall	DB		67023	76480	78536	85115*a*
Strip-till	0	Control (no P)			72368	70724	82237	83471*a*
	30	Spring	SB		70183	74836	83059	83471*a*
	60	Spring	SB		68257	74424	81415	85938*a*
	30	Fall	DB		64953	70724	81415	81826*a*
	60	Fall	DB		66612	75247	84704	82237*a*
Conventional					66483	75000	78947	83498
Strip-till					68475	73191	82566	83388
	0	Control (no P)			70312	71957	81826	82648
	30	Spring	SB		69631	74835	82031	82854
	60	Spring	SB		64145	74013	78947	84361
	30	Fall	DB		66488	73807	79359	83676
	60	Fall	DB		66817	75863	81620	83676
ANOVA				Df	Pr>F			
Fert				4	0.6624	0.5470	0.1124	0.4957
Tillage				1	0.5418	0.2255	0.1096	0.8686
Crop*Tillage				4	0.8049	0.5975	0.3683	0.0093*
Coeff Var (C.V.)					12	6	5	3

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix F.2 Residue ground cover: effect of tillage practice at Carman 2015, 2016 and Portage la Prairie 2015, 2016 (Chapter 3)

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			%[e]				
Conventional	0	Control (no P)		31	17	33	47	32
	30	Spring	SB	32	15	30	51	32
	60	Spring	SB	29	15	37	51	33
	30	Fall	DB	41	12	30	45	32
	60	Fall	DB	28	17	34	49	32
Strip-till	0	Control (no P)		45	22	46	54	42
	30	Spring	SB	41	27	49	49	42
	60	Spring	SB	55	29	55	41	45
	30	Fall	DB	55	30	52	50	47
	60	Fall	DB	53	25	49	54	45
Conventional				32*Bb*[f]	15*Cb*	33*Bb*	49*Aa*	32
Strip-till				50*Aa*	27*Ba*	50*Aa*	50*Aa*	44
	0	Control (no P)		38	39	20	50	37
	30	Spring	SB	36	40	21	50	37
	60	Spring	SB	42	46	22	46	39
	30	Fall	DB	48	41	21	48	39
	60	Fall	DB	41	42	21	52	39
Site-year				41	21	41	49	

ANOVA	Df	Pr>F
Fert	4	0.6568
Tillage	1	<.0001*
Tillage*Fert	4	0.7027
Site-year	3	<.0001*
Site-year*Fert	12	0.6157
Site-year*Tillage	3	0.0134*
Site-year*Tillage*Fert	12	0.3849
Coeff Var (C.V.)		40

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] Percent ground cover calculated using *Assess 2.0 Image Analysis Software for Plant Disease Quantification* by Lakhdar Lamari ® 2008.
[f] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix F.3 Symptoms of phosphorus deficiency as a purpling colouration due to anthocyanin production in young corn leaves at V3 stage, corn in strip-till, at Carman in 2015.

Appendix F.4 Normalized Difference Vegetation Index

Corn normalized difference vegetation index (NDVI) was assessed using a GreenSeeker® handheld crop sensor at V7 growth stage in 2015 and at V5 growth stage in 2016. Two passes were made on the two middle rows for the entire plot length and an average of the readings was recorded to represent plant biomass density. In 2015, NDVI differences between fertilizer treatments and the unfertilized control were significant but smaller compared to differences observed in 2016 since the canopy has already closed up at the V7 stage. In 2016, NDVI measurements were taken at an earlier stage of corn development in order to capture larger plant biomass density differences. Since NDVI measurements were taken at two different stages of development, 2015-2016 site-years cannot be combined for statistical analysis.

Appendix F.4, continued Normalized Difference Vegetation Index: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]					
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman[e]	Portage[e]	Carman[f]	Portage[f]	All sites	All sites
	P_2O_5			2015	2015	2016	2016	2015	2016
	kg ha^{-1}			**NDVI**					
Conventional	0	Control (no P)		0.66	0.74	0.42	0.48	0.70	0.45
	30	Spring	SB	0.71	0.75	0.53	0.52	0.73	0.53
	60	Spring	SB	0.70	0.75	0.53	0.49	0.73	0.51
	30	Fall	DB	0.68	0.74	0.41	0.55	0.71	0.48
	60	Fall	DB	0.70	0.75	0.45	0.55	0.72	0.50
Strip-till	0	Control (no P)		0.62	0.73	0.35	0.50	0.67	0.42
	30	Spring	SB	0.71	0.75	0.49	0.53	0.73	0.51
	60	Spring	SB	0.71	0.74	0.47	0.56	0.72	0.52
	30	Fall	DB	0.64	0.74	0.39	0.49	0.69	0.44
	60	Fall	DB	0.70	0.74	0.40	0.47	0.72	0.44
Conventional				0.69	0.75	0.47	0.52	0.72	0.49
Strip-till				0.67	0.74	0.42	0.51	0.71	0.46
	0	Control (no P)		0.64*Bb*[g]	0.74*Aa*	0.39*Bb*	0.49*Aa*	0.69	0.44
	30	Spring	SB	0.71*Ba*	0.75*Aa*	0.51*Aa*	0.53*Aa*	0.73	0.52
	60	Spring	SB	0.70*Ba*	0.74*Aa*	0.50*Aa*	0.53*Aa*	0.72	0.51
	30	Fall	DB	0.66*Bb*	0.74*Aa*	0.40*Bb*	0.52*Aa*	0.70	0.46
	60	Fall	DB	0.70*Ba*	0.74*Aa*	0.42*Bb*	0.51*Aa*	0.72	0.47
Site-year				0.68	0.74	0.44	0.51		

ANOVA	Df	Pr>F	
Fert	4	<.0001*	<.0001*
Tillage	1	0.0585	0.1755
Tillage*Fert	4	0.2598	0.4350
Site-year	1	<.0001*	0.0039*
Site-year*Fert	4	0.0001*	0.0151*
Site-year*Tillage	1	0.3481	0.3099
Site-year*Tillage*Fert	4	0.2438	0.0835
Coeff Var (C.V.)		6	16

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] NDVI values recorded at V7 corn stage.
[f] NDVI values recorded at V5 corn stage.
[g] A-B Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix G

Mid to Late Season Crop Measurements (Chapter 3)

Appendix G.1a Days to 50% pollen shed

The number of days from planting until the day when ≥50% of the plants in the two center rows of each plot had reached 50% pollen shed was recorded for each plot. Days to 50% pollen shed were assessed following full tassel emergence. In 2015, the maturity ratings assigned in the field suggest that 50% pollen shed occurred prior to silking. However, pollen shed normally begins 2-3 d after complete tassel emergence from the whorl and silks are pollinated within 4-10 d after tassel emergence (Manitoba Corn Growers Association 2014). Therefore, if pollen shed occurred after the silks developed it would have caused synchronous pollen well, drying out the silks. However, silks did not dry out and fertilization occurred, indicating that days to 50% pollen shed may not have been the most accurate estimate of crop maturity in 2015, and rather days to silking can be a better predictor of corn developmental stage.

Appendix G.1a, continued Days to 50% pollen shed: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			DAP[e]				
Conventional	0	Control (no P)		63	64	72	69	67*b*
	30	Spring	SB	64	64	71	68	67*b*
	60	Spring	SB	63	64	71	68	66*b*
	30	Fall	DB	64	65	74	68	67*ab*
	60	Fall	DB	63	64	72	68	67*b*
Strip-till	0	Control (no P)		66	65	76	69	69*a*
	30	Spring	SB	64	64	71	68	67*b*
	60	Spring	SB	64	64	71	68	67*b*
	30	Fall	DB	64	64	73	68	67*b*
	60	Fall	DB	64	64	72	68	67*b*
Conventional				64	64	72	68	67
Strip-till				64	64	73	68	67
	0	Control (no P)		65*Ca*[f]	64*Ca*	74*Aa*	69*Ba*	68
	30	Spring	SB	64*Ca*	64*Ca*	71*Ac*	68*Ba*	67
	60	Spring	SB	63*Ca*	64*Ca*	71*Ac*	68*Ba*	66
	30	Fall	DB	64*Ca*	64*Ca*	74*Aab*	68*Ba*	67
	60	Fall	DB	63*Ca*	64*Ca*	72*Abc*	68*Ba*	67
Site-year				64	64	72	68	

ANOVA	Df	Pr>F
Fert	4	<.0001*
Tillage	1	0.1307
Tillage*Fert	4	0.0205*
Site-year	3	<.0001*
Site-year*Fert	12	0.0016*
Site-year*Tillage	3	0.6264
Site-year*Tillage*Fert	12	0.1396
Coeff Var (C.V.)		6

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] DAP, days after planting.
[f] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Appendix G.2 Visual differences in ear development and silking on 2015 July 28 at Carman (L) 60 kg P_2O_5 ha^{-1} spring side-banded MAP (R) unfertilized control, conventional tillage

Appendix G.3a Late season cob moisture recorded from R4 until harvest at Carman 2015: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Dates[a]					
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Sep. 01	Sep. 12	Sep. 21	Sep. 28	Oct. 05	Oct. 13
	P_2O_5								
	kg ha^{-1}			g kg^{-1}					
Conventional	0	Control (no P)		53	39	32	28	24	24
	30	Spring	SB	52	35	30	27	23	23
	60	Spring	SB	53	34	29	27	23	23
	30	Fall	DB	52	37	30	29	23	23
	60	Fall	DB	52	36	30	28	24	24
Strip-till	0	Control (no P)		53	38	32	28	25	25
	30	Spring	SB	52	34	29	28	22	22
	60	Spring	SB	52	35	29	26	24	24
	30	Fall	DB	52	34	31	27	22	22
	60	Fall	DB	53	37	30	28	23	23
Conventional				52	36	30	28	23	23
Strip-till				52	35	30	27	23	23
	0	Control (no P)		53	38	32	28	24	24
	30	Spring	SB	52	34	30	27	22	22
	60	Spring	SB	53	35	29	26	23	23
	30	Fall	DB	52	36	31	28	23	23
	60	Fall	DB	52	36	30	28	24	24
Day				52*A*[e]	36*B*	30*C*	28*D*	23*E*	23*E*

ANOVA	Df	Pr>F
Day	5	<.0001*
Day*Tillage	5	0.8185
Day*Fert	20	0.2139
Day*Tillage*Fert	20	0.4987
Coeff Var (C.V.)		32

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-E Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix G.3b Late season cob moisture recorded from R4 until harvest at Portage 2015: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Dates[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Sep. 03	Sep. 21	Sep. 28	Oct. 05	Oct. 13
	P_2O_5							
	kg ha^{-1}			g kg^{-1}				
Conventional	0	Control (no P)		53	39	32	31	31
	30	Spring	SB	54	38	33	30	31
	60	Spring	SB	52	39	32	30	31
	30	Fall	DB	52	40	32	31	29
	60	Fall	DB	52	38	32	31	32
Strip-till	0	Control (no P)		53	39	32	31	32
	30	Spring	SB	53	39	32	31	28
	60	Spring	SB	52	39	32	31	27
	30	Fall	DB	52	38	32	31	27
	60	Fall	DB	52	37	32	31	28
Conventional				53*Aa*[e]	39*Ba*	32*Ca*	31*Ca*	31*Ca*
Strip-till				52*Aa*	38*Ba*	32*Ca*	31*Ca*	28*Db*
	0	Control (no P)		53	39	32	31	32
	30	Spring	SB	53	39	33	31	30
	60	Spring	SB	52	39	32	31	29
	30	Fall	DB	52	39	32	31	28
	60	Fall	DB	52	38	32	31	30
Day				53	39	32	31	30

ANOVA	Df	Pr>F
Day	4	<.0001*
Day*Tillage	4	0.0070*
Day*Fert	16	0.4519
Day*Tillage*Fert	16	0.8017
Coeff Var (C.V.)		24

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-D Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Appendix G.3c Late season cob moisture recorded from R4 until harvest at Carman 2016: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Dates[a]						
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Aug. 16	Aug. 23	Sep. 01	Sep. 08	Sep. 13	Sep. 20	Sep. 28
	P_2O_5									
	kg ha^{-1}			g kg^{-1}						
Conventional	0	Control (no P)		60	57	54	51	44	38	34
	30	Spring	SB	58	56	53	49	41	36	31
	60	Spring	SB	58	56	53	49	40	38	33
	30	Fall	DB	61	57	54	52	46	38	36
	60	Fall	DB	59	57	53	50	45	38	35
Strip-till	0	Control (no P)		61	59	55	53	47	40	34
	30	Spring	SB	59	56	54	49	42	36	34
	60	Spring	SB	58	57	54	50	42	38	31
	30	Fall	DB	61	58	56	54	47	43	33
	60	Fall	DB	61	58	55	53	47	40	36
Conventional				59	57	53	50	43	38	33
Strip-till				60	58	55	52	45	39	34
	0	Control (no P)		61*Aa*[e]	58*Aa*	54*Ba*	52*Bab*	45*Ca*	39*Dab*	34*Eab*
	30	Spring	SB	59*Aa*	56*ABa*	54*Ba*	49*Cc*	41*Db*	36*Ec*	32*Fb*
	60	Spring	SB	58*Aa*	56*Aa*	54*Ba*	49*Cbc*	41*Db*	38*Ebc*	32*Fb*
	30	Fall	DB	61*Aa*	57*Ba*	55*BCa*	53*Ca*	46*Da*	41*Ea*	34*Fab*
	60	Fall	DB	60*Aa*	57*Aa*	54*Ba*	51*Cabc*	46*Da*	39*Eabc*	35*Fa*
Day				59	57	54	51	44	38	34

ANOVA	Df	Pr>F
Day	6	<.0001*
Day*Tillage	6	0.2250
Day*Fert	24	0.0368*
Day*Tillage*Fert	24	0.4204
Coeff Var (C.V.)		20

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-F Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix G.3d Late season cob moisture recorded from R4 until harvest at Portage 2016: effect of tillage practice and monoammonium phosphate rate, placement and timing

Treatment				Dates[a]						
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Aug. 16	Aug. 23	Aug. 31	Sep. 07	Sep. 14	Sep. 21	Sep. 28
	P_2O_5									
	—kg ha^{-1}—			g kg^{-1}						
Conventional	0	Control (no P)		61	60	55	51	47	36	32
	30	Spring	SB	59	59	54	50	43	34	29
	60	Spring	SB	59	59	54	51	45	34	31
	30	Fall	DB	59	59	53	49	41	31	29
	60	Fall	DB	60	59	54	50	41	33	29
Strip-till	0	Control (no P)		60	59	54	50	45	33	31
	30	Spring	SB	60	59	54	50	42	32	29
	60	Spring	SB	59	58	53	49	42	33	28
	30	Fall	DB	59	59	54	50	44	33	30
	60	Fall	DB	60	59	54	50	43	32	29
Conventional				60	59	54	50	44	33	30
Strip-till				60	59	54	50	43	33	30
	0	Control (no P)		60	60	54	51	46	34	32
	30	Spring	SB	60	59	54	50	43	33	29
	60	Spring	SB	59	58	54	50	43	33	30
	30	Fall	DB	59	59	53	50	43	32	30
	60	Fall	DB	60	59	54	50	42	33	29
Day				60*A*[e]	59*A*	54*B*	50*C*	43*D*	33*E*	30*F*

ANOVA	Df	Pr>F
Day	6	<.0001*
Day*Tillage	6	0.8494
Day*Fert	24	0.8160
Day*Tillage*Fert	24	0.7439
Coeff Var (C.V.)		24

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-F Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P< 0.05$.

Appendix H

Late Season Crop Measurements (Chapter 3)

Appendix H.1. Test weight at harvest: effect of tillage practice and monoammonium phosphate rate, placement and timing

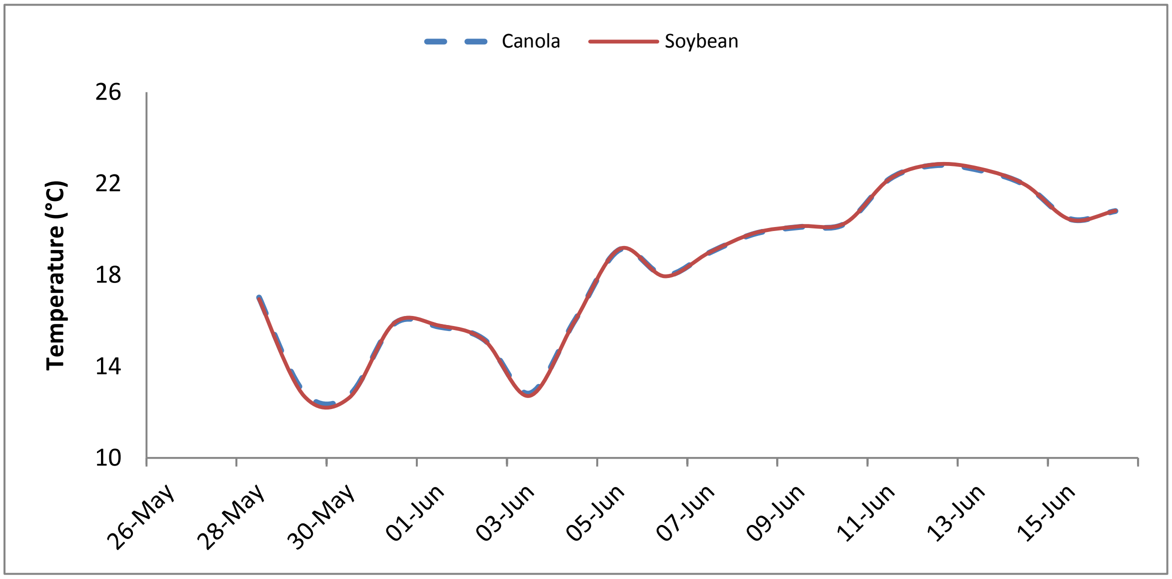
Treatment				Site-year[a]				
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman	Portage	Carman	Portage	All sites
	P_2O_5			2015	2015	2016	2016	2015-2016
	kg ha^{-1}			g 0.5 L^{-1}				
Conventional	0	Control (no P)		339*Aa*[e]	312*Babc*	313*Ba*	344*Aa*	327
	30	Spring	SB	349*Aa*	300*Babc*	318*Ba*	345*Aa*	328
	60	Spring	SB	351*Aa*	295*Cbc*	325*Ba*	344*ABa*	329
	30	Fall	DB	343*Aa*	294*Bbc*	310*Ba*	356*Aa*	325
	60	Fall	DB	344*Aa*	319*Ba*	313*Ba*	348*Aa*	331
Strip-till	0	Control (no P)		340*Aa*	288*Cc*	312*Ba*	348*Aa*	322
	30	Spring	SB	350*Aa*	293*Cbc*	321*Ba*	346*Aa*	327
	60	Spring	SB	349*Aa*	302*Babc*	310*Ba*	351*Aa*	328
	30	Fall	DB	347*Aa*	314*Bab*	305*Ba*	351*Aa*	329
	60	Fall	DB	348*Aa*	303*Babc*	304*Ba*	354*Aa*	327
Conventional				345	304	316	347	328
Strip-till				347	300	310	350	327
	0	Control (no P)		340	300	312	346	324
	30	Spring	SB	349	296	320	346	328
	60	Spring	SB	350	298	317	348	328
	30	Fall	DB	345	304	307	353	327
	60	Fall	DB	346	311	308	351	329
Site-year				346	302	313	349	

ANOVA	Df	Pr>F
Fert	4	0.4254
Tillage	1	0.5677
Tillage*Fert	4	0.4815
Site-year	3	<.0001*
Site-year*Fert	12	0.0291*
Site-year*Tillage	3	0.5846
Site-year*Tillage*Fert	12	0.0166*
Coeff Var (C.V.)		

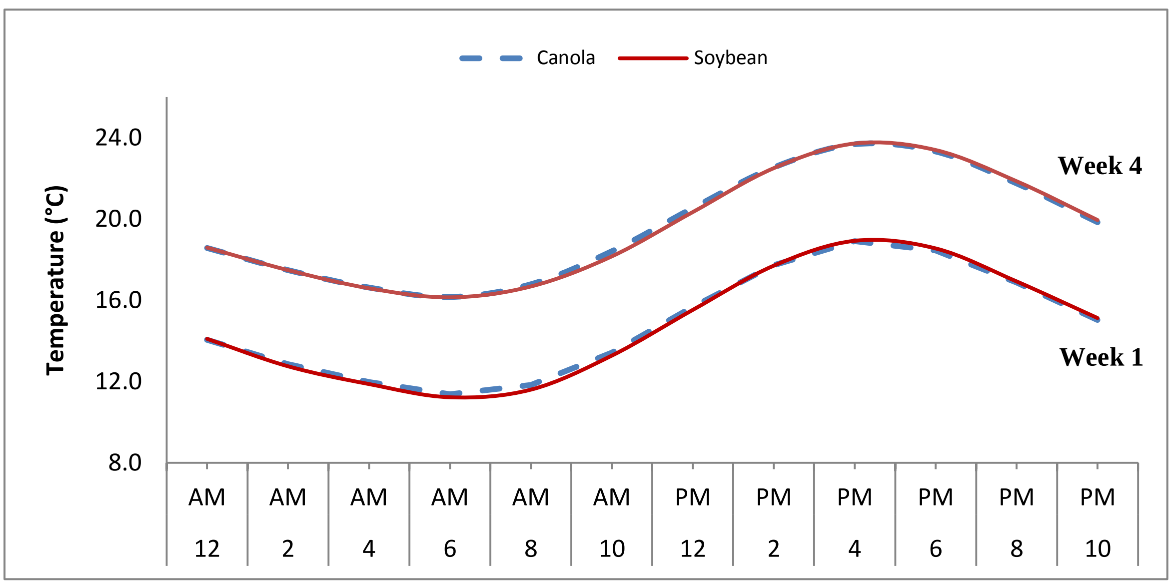
[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] A-C Least square mean values followed by the same upper case letter (within rows) are not significantly different, determined by Tukey-Kramer grouping; a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix I

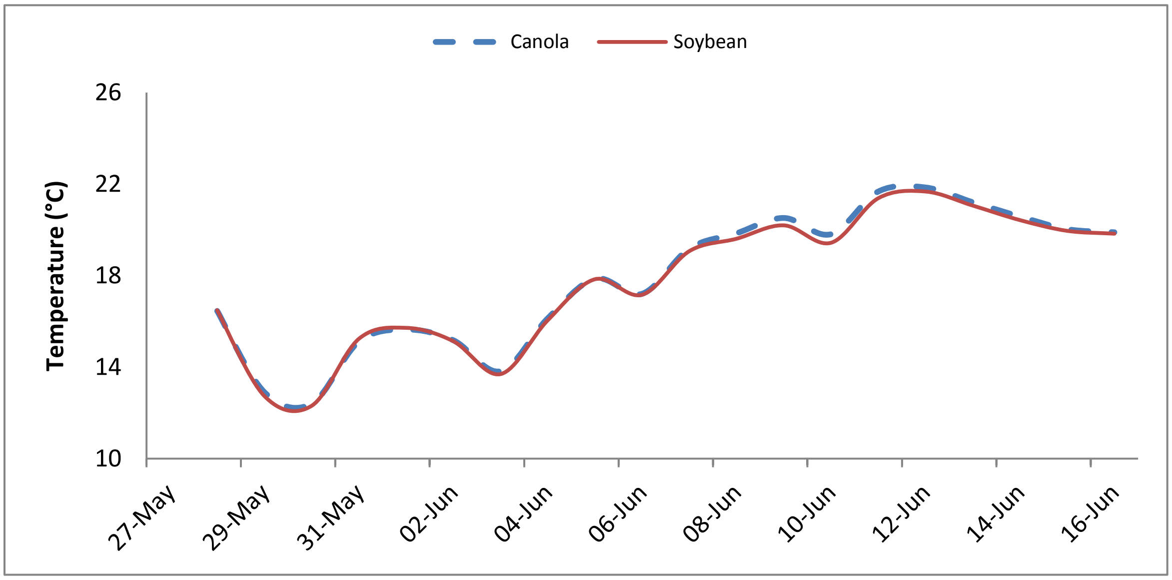
Soil Temperature Data (Chapter 2 and Chapter 3)



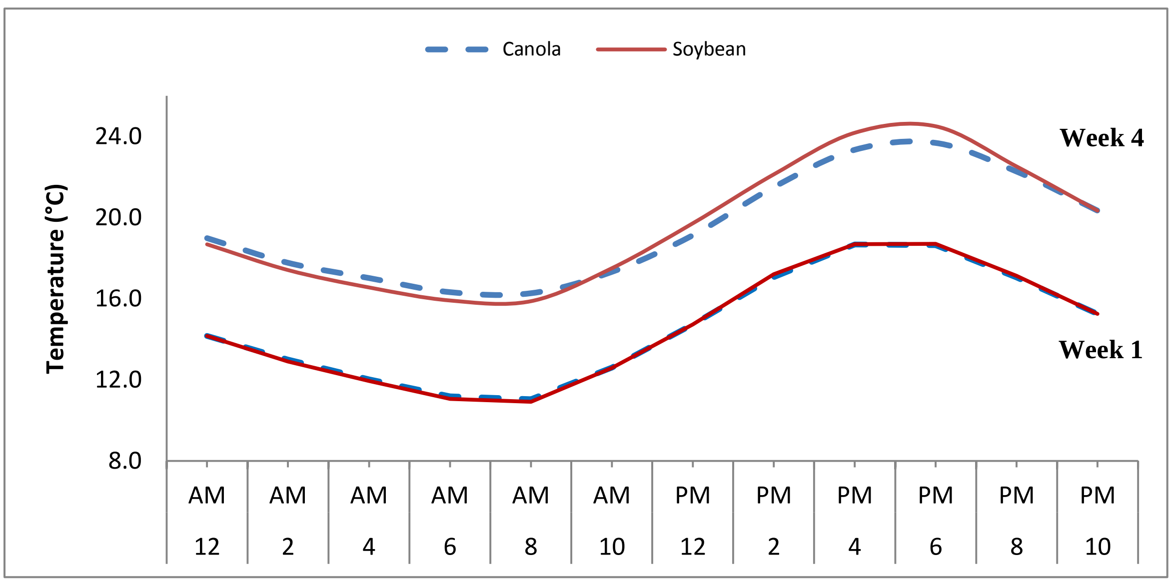
Appendix I.1a Average 3-week soil temperature for corn after canola and soybean preceding crop treatments in 2015 at Carman, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 2).



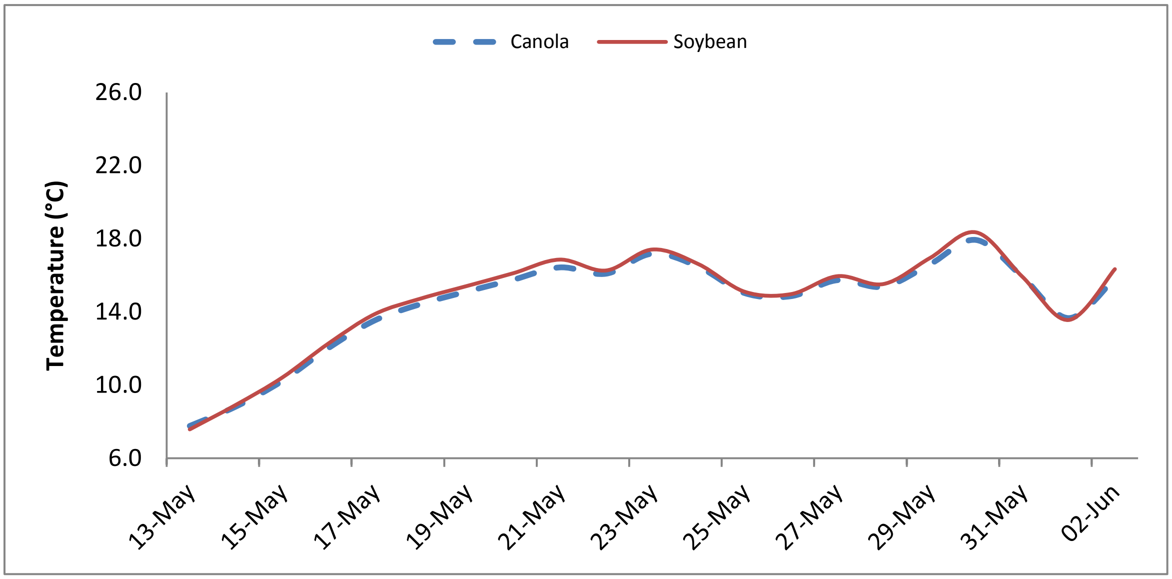
Appendix I.1b Average night-time vs. day-time soil temperature for corn after canola and soybean preceding crop treatments in 2015 at Carman, MB during between 2015 May 26-June 01 (Week 1) and 2015 June 16-22 (Week 4) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 2).



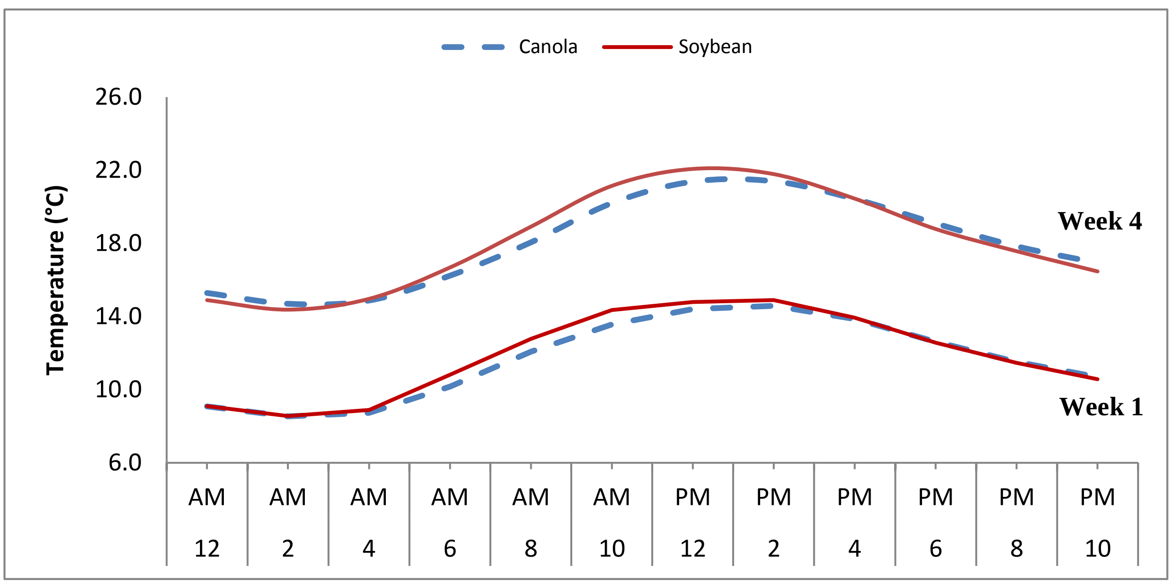
Appendix I.2a Average 3-week soil temperature for corn after canola and soybean preceding crop treatments in 2015 at Stephenfield, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 2).



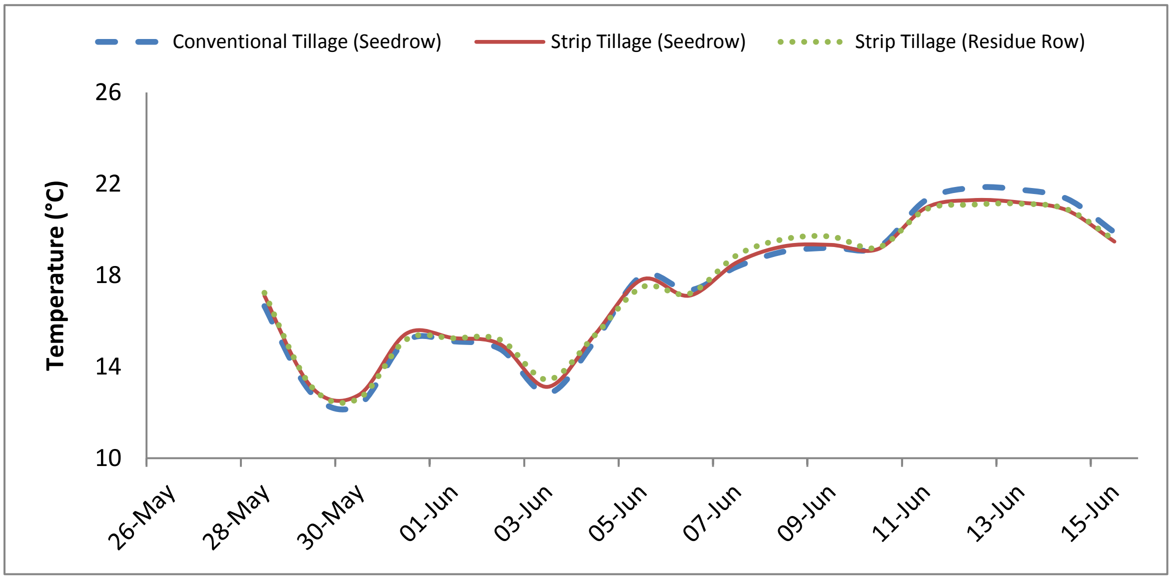
Appendix I.2b Average night-time vs. day-time soil temperature for corn after canola and soybean preceding crop treatments in 2015 at Stephenfield, MB during between 2015 May 27-June 02 (Week 1) and 2015 June 17-23 (Week 4) monitored using Thermochron® Button® devices (DS1921G) buried at 5 cm depth (Chapter 2).



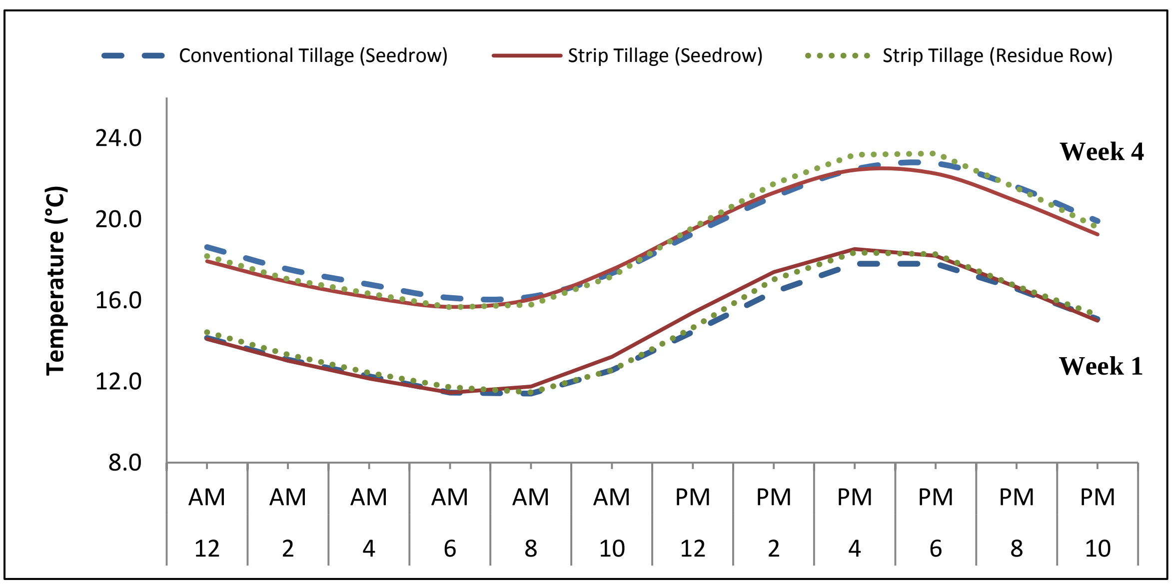
Appendix I.3a Average 3-week soil temperature for corn after canola and soybean preceding crop treatments in 2016 at Carman, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 2).



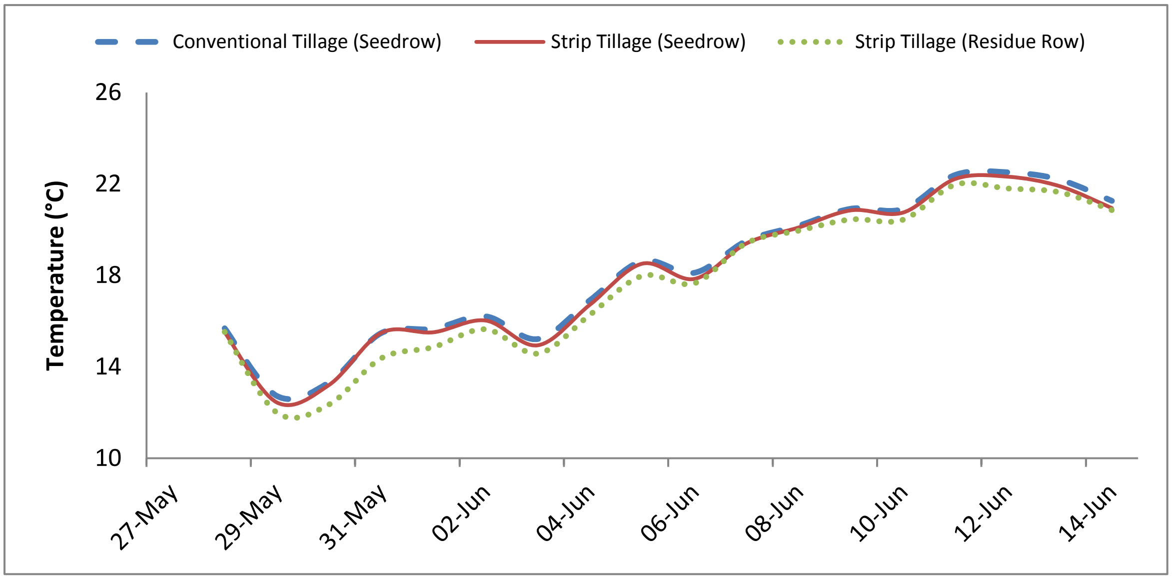
Appendix I.3b Average night-time vs. day-time soil temperatures for corn after canola and soybean preceding crop treatments in 2016 at Carman, MB during between 2016 May 13-19 (Week 1) and 2016 June 03-09 (Week 4) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 2).



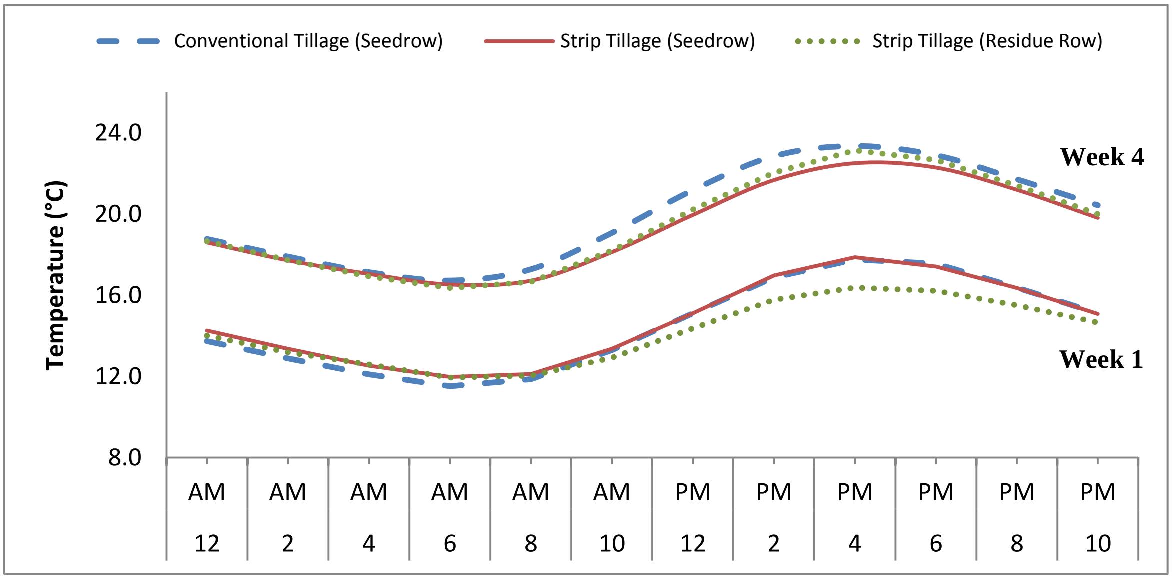
Appendix I.4a Average 3-week soil temperature for corn planted in conventional tillage and strip-tillage in 2015 at Carman, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



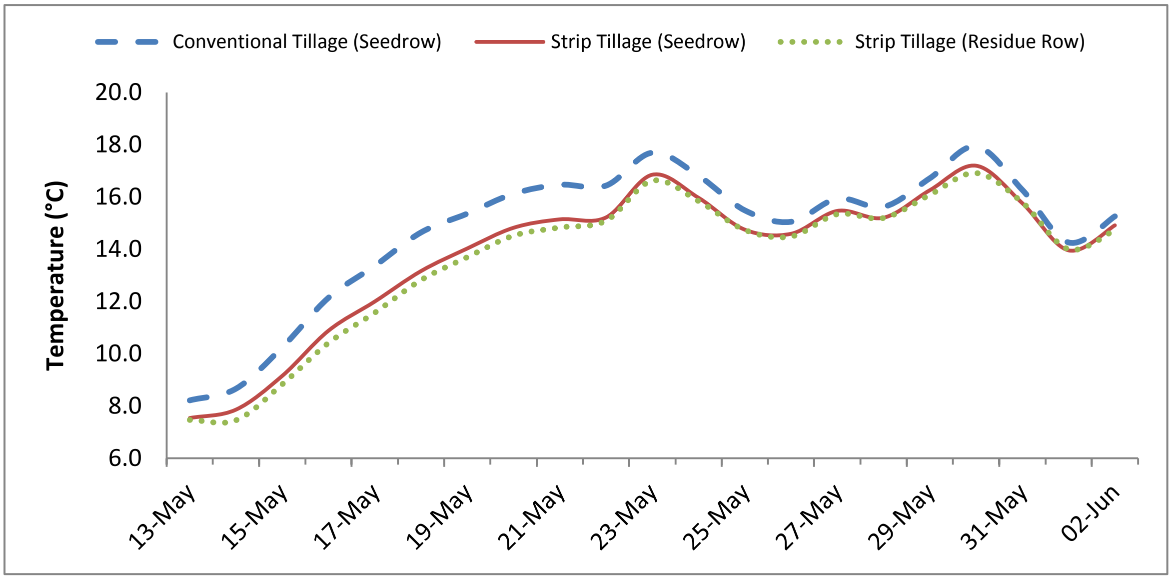
Appendix I.4b Average night-time vs. day-time soil temperatures for corn planted in conventional tillage and strip-till in 2015 at Carman, MB during between 2015 May 26-June 01 (Week 1) and 2015 June 16-22 (Week 4) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



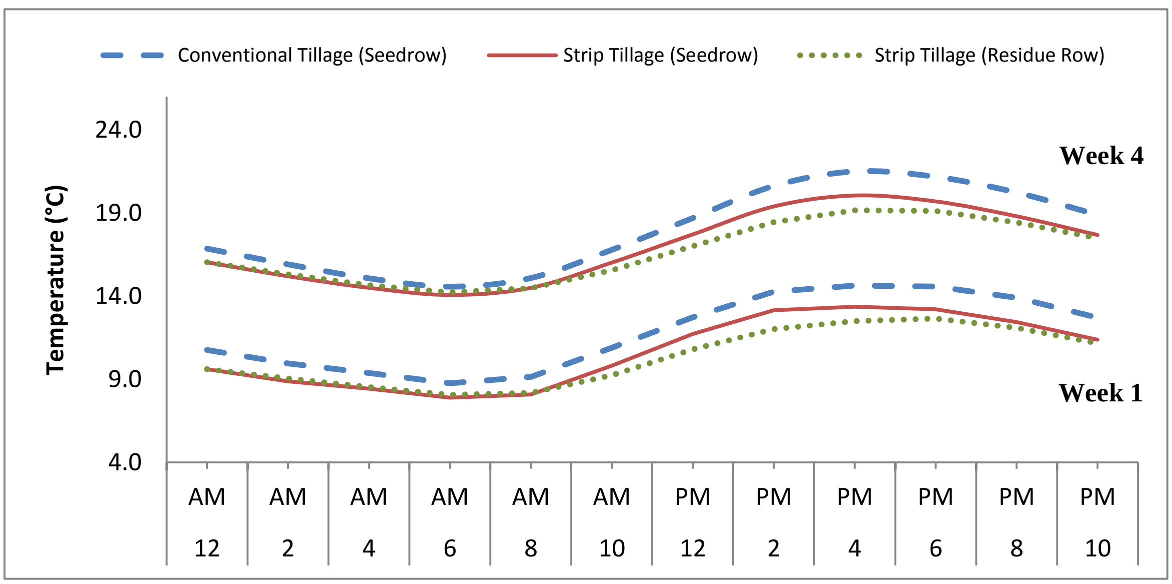
Appendix I.5a Average 3-week soil temperature for corn planted in conventional tillage and strip-tillage in 2015 at Portage la Prairie, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



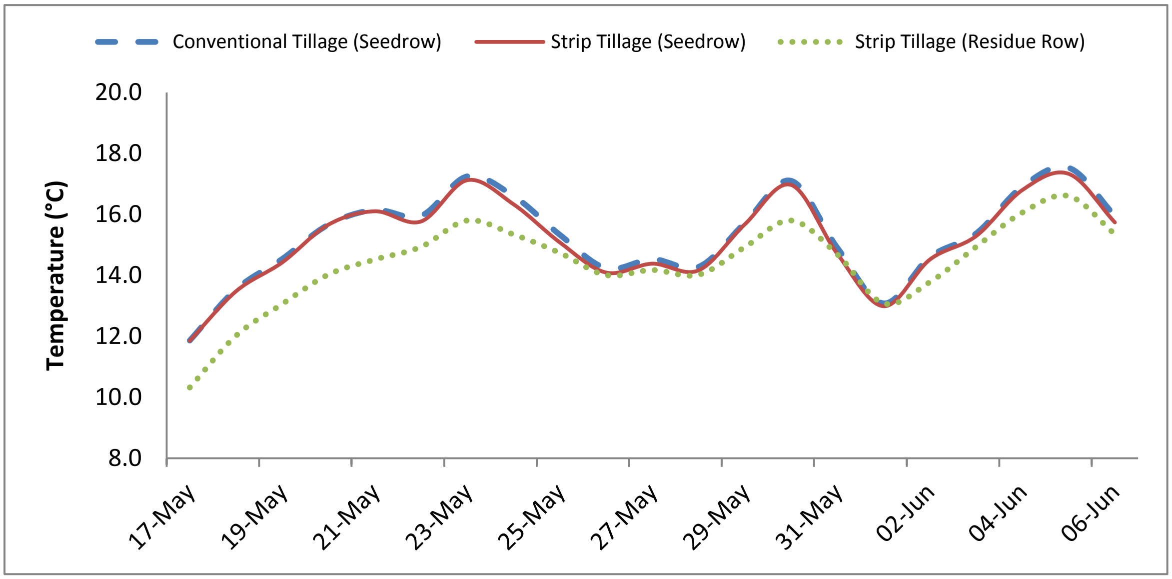
Appendix I.5b Average night-time vs. day-time soil temperatures for corn planted in conventional tillage and strip-till in 2015 at Portage la Prairie, MB during between 2015 May 27-June 02 (Week 1) and 2015 June 17-23 (Week 4) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



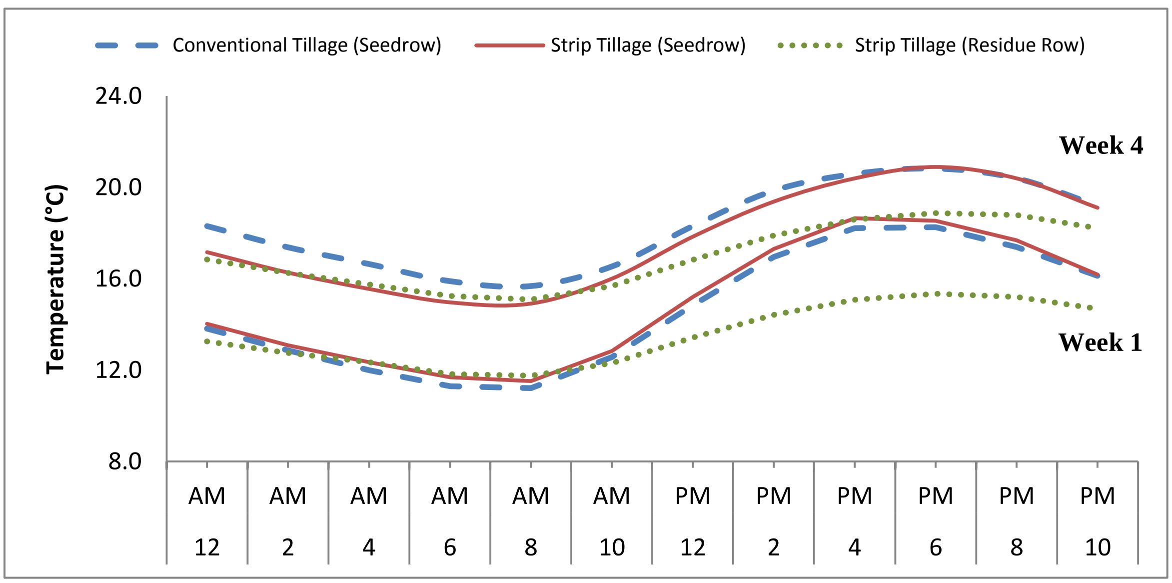
Appendix I.6a Average 3-week soil temperature for corn planted in conventional tillage and strip-tillage in 2016 at Carman, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



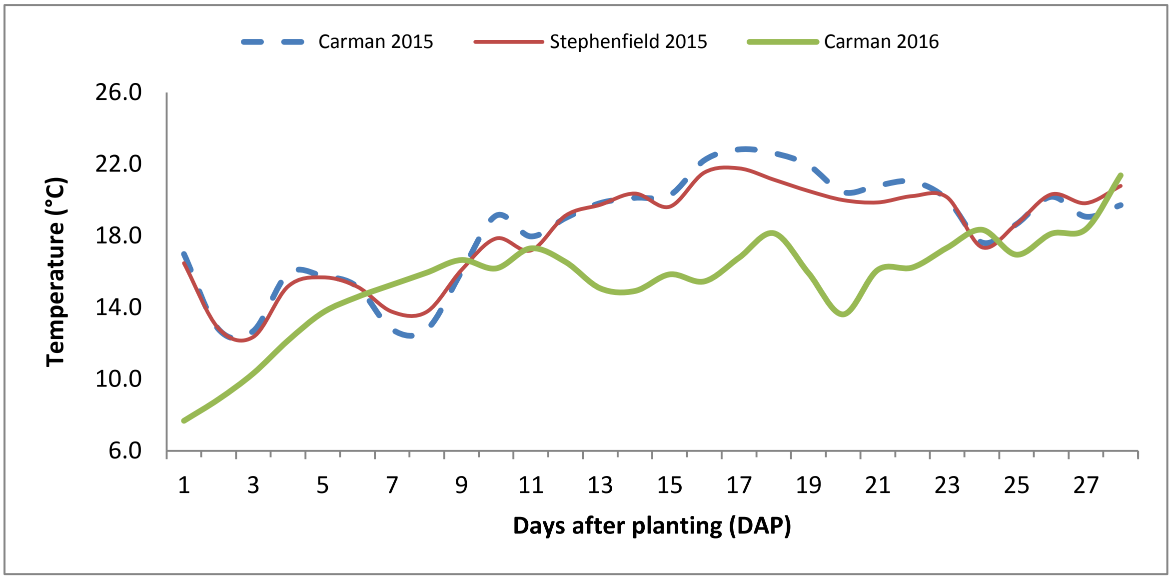
Appendix I.6b Average night-time vs. day-time soil temperatures for corn planted in conventional tillage and strip-till in 2016 at Carman, MB during between 2015 May 13-19 (Week 1) and 2015 June 03-09 (Week 4) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



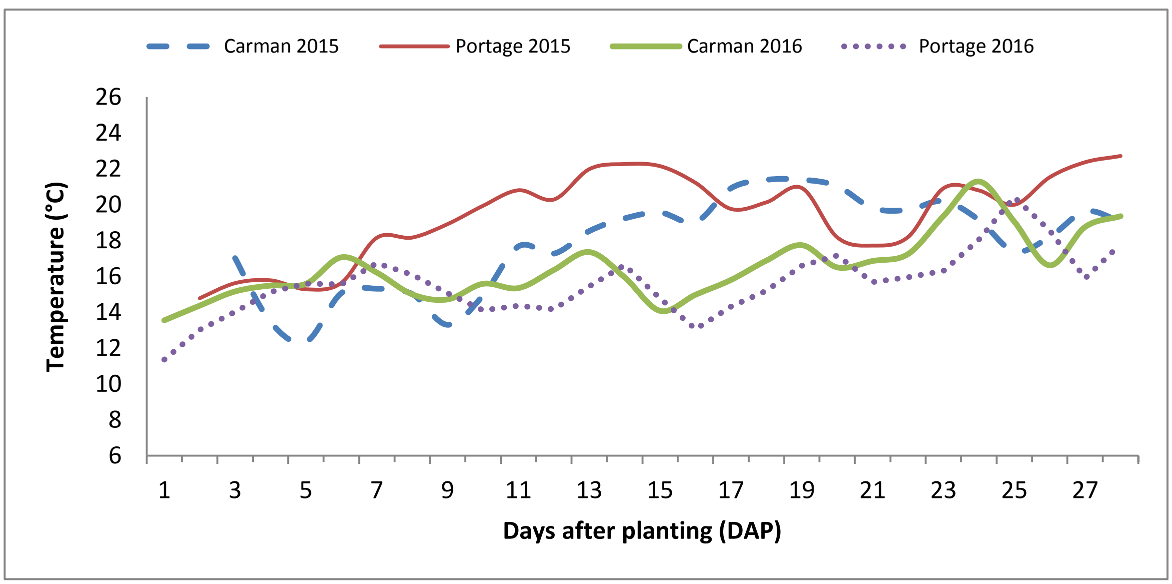
Appendix I.7a Average 3-week soil temperature for corn planted in conventional tillage and strip-tillage in 2016 at Portage la Prairie, MB monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



Appendix I.7b Average night-time vs. day-time soil temperatures for corn planted in conventional tillage and strip-till in 2016 at Portage la Prairie, MB during between 2015 May 17-23 (Week 1) and 2015 June 07-13 (Week 4) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).



Appendix I.8a Average soil temperature seven days after planting at Carman 2015 (May 26-June 22), Stephenfield, MB (May 27-June 23) and Carman 2016 (May 13-June 02) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 2).



Appendix I.8b Average soil temperature seven days after planting at Carman 2015 (May 26-June 22), Portage la Prairie, MB 2015 (May 27-June 23), Carman 2016 (May 13-June 09) and Portage la Prairie, MB 2016 (May 17-June 13) monitored using Thermochron® iButton® devices (DS1921G) buried at 5 cm depth (Chapter 3).

Appendix J

Moisture Budget (Chapter 2 and Chapter 3)

Appendix J Spring soil moisture, total growing season precipitation, moisture crop demand and growing season water balance for all site-years (Chapter 2 and Chapter 3)

Site-year	Available Soil Moisture (Spring)[a]	Growing Season Precipitation	Growing Season Crop Water Demand[b]	Growing Season Water Balance[c]
	mm			
Chapter 2				
Carman 2015	68	297[d]	530	-165
Stephenfield 2015	82	264[d]	530	-184
Carman 2016	95	404[d]	530	-31
Chapter 3				
Carman 2015	62	297[e]	530	-171
Portage la Prairie 2015	144	369[e]	530	-17
Carman 2016	97	404[e]	530	-29
Portage la Prairie 2016	120	385[e]	530	-25

[a] Soil moisture in spring calculated from Giddings samples collected to a 120 cm depth before or soon after planting at each site-year.
[b] Moisture crop demand based on 7519 kg ha^{-1} corn crop grown in Manitoba (Manitoba Corn Growers Association 2014).
[c] Growing season water balance calculated as (available soil moisture in the spring + growing season precipitation) – growing season crop water demand.
[d] Total precipitation data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for Carman 2015 from May 25 Oct. 15, Carman 2016 from May 12-Oct. 05 and from a a WatchDog 1000 Series Micro Station for Stephenfield 2015 from May 27-Oct. 14,
[e] Total precipitation data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for Carman 2015 between May 25 Oct.16, Portage la Prairie 2015 between May 26-Oct.19, Carman 2016 between May 12-Oct. 05 and Portage la Prairie 2016 between May 16-Oct. 06.

Appendix K

Crop Damage (Chapter 2 and Chapter 3)

Appendix K.1a Bird feeding damage to corn ears: shredded husk leaves and damaged tips at Portage la Prairie in 2015 (Chapter 3).

Appendix K.1b Bird feeding damage to corn ears: missing and damaged kernels, weathered, mouldy cob tissue at Portage la Prairie in 2015 (Chapter 3).

Appendix K.2a Percent green snap damage at Carman 2016: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band (Chapter 2)

Treatment					Site-year[a]
Preceding Crop	Fertilizer Treatment			Products[b]	Carman
	P_2O_5	S	Zn		2016
	kg ha^{-1}				% damage
Canola	0	0	0	Control (no starter)	66*ab*[c]
	30	7.5	0	MAP + AS	55*abc*
	60	15	0	MAP + AS	50*bc*
	30	7.5	0.75	MESZn	45*c*
	60	15	1.5	MESZn	46*c*
Soybean	0	0	0	Control (no starter)	67*a*
	30	7.5	0	MAP + AS	47*c*
	60	15	0	MAP + AS	47*c*
	30	7.5	0.75	MESZn	59*abc*
	60	15	1.5	MESZn	50*abc*
Canola					52
Soybean					54
	0	0	0	Control (no starter)	66
	30	7.5	0	MAP + AS	51
	60	15	0	MAP + AS	49
	30	7.5	0.75	MESZn	52
	60	15	1.5	MESZn	48

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.4847
Crop*Fert	4	0.0440*
Coeff Var (C.V.)		20

[a] Least square means (LSmeans) recorder from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulfate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix K.2b Percent green snap damage at Carman 2016: effect of tillage practice and monoammonium phosphate rate, placement and timing (Chapter 3)

Treatment				Site-year[a]
Tillage[b]	Fertilizer Rate[c]	Timing	Placement[d]	Carman
	P_2O_5			2016
	kg ha^{-1}			% damage
Conventional	0	Control (no P)		67
	30	Spring	SB	53
	60	Spring	SB	42
	30	Fall	DB	65
	60	Fall	DB	62
Strip-till	0	Control (no P)		65
	30	Spring	SB	49
	60	Spring	SB	44
	30	Fall	DB	68
	60	Fall	DB	62
Conventional				58
Strip-till				58
	0	Control (no P)		66*a*[e]
	30	Spring	SB	51*b*
	60	Spring	SB	43*b*
	30	Fall	DB	66*a*
	60	Fall	DB	62*a*

ANOVA	Df	Pr>F
Fert	4	<.0001*
Crop	1	0.9913
Crop*Fert	4	0.7913
Coeff Var (C.V.)		22

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] All tillage practices performed in the fall prior to corn planting in the spring.
[c] All fertilizer treatments applied as monoammonium phosphate (MAP, 11-52-0-0).
[d] Deep band (DB) 10 to 13 cm; Side band (SB) 5 cm to the side and 2.5 cm below the seed.
[e] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix K.2c Wind damage to corn plants: green snap at Carman in 2016 (Chapter 2 and Chapter 3).

Appendix K.3

Hail damage generally affects yield by reducing the plant stand and by causing defoliation and loss of photosynthetic leaf area. Hail damage causes the most yield loss during rapid plant growth, with the greatest potential for damage at the tasseling stage. Following tasseling and as the plant continues to approach maturity, hail causes progressively less yield loss. In addition to defoliation damage, plants may be broken off and should be account for in the yield loss estimates. However, if plants are not broken off but rather the stems are bruised, the likelihood of infection is greater, which may account for a very small portion of yield loss at harvest.

Appendix K.3a Hail damage to corn plants: shredded leaves and damaged cobs at Portage la Prairie in 2016 (Chapter 3).

Appendix K.3b Hail damage to corn plants: shredded leaves and damaged cobs at Portage la Prairie in 2016 (Chapter 3).

Appendix L

Mosaic MicroEssentials® SZ Study: Kelburn Farm, St. Adolphe, Manitoba (2015)

Appendix L.1. Background and Objectives

Originally, the site at Kelburn Farm near St. Adolphe was set up as a site-year to be included in the rotation study. Unfortunately, due to quarantine regulations imposed by the Canadian Food Inspection Agency (CFIA), soil sampling and most field activities were limited and the St. Adolphe location could not be used as a full experiment site. Instead, it hosted a Mosaic MicroEssentials® SZ Study, where MESZn was applied at two different rates on canola and soybean stubble. The objectives of the study were to evaluate corn yield and grain moisture response to side banded starter fertilizer when corn followed canola vs. soybean.

Appendix L.2. Site Description and Characteristics

The experiment site was located at the Kelburn Farm near St. Adolphe (49°41' N, 97° 7' W), where Olsen extractable soil test P concentrations ranged from 24 to 63 mg kg^{-1}. The high soil test P concentrations were expected, considering that Kelburn Farm produced beef cattle in the past and some areas of the Farm were heavily manured during that period. Prior to the corn test crop year, 24 soil samples were collected in the fall (0-15 and 15-60 cm depths) to determine basal rates of any additional nutrients, including potassium (K) or micronutrients other than zinc (Zn). Soil was sampled once more in the spring before planting corn and three cores were collected at two depths (0-15 and 15-60 cm) from each replicate of each crop block. Soil samples were sent to AgVise Laboratories (Northwood, ND, USA) to measure residual nitrate-N and determine nitrogen (N) fertilizer requirements. Soil texture was determined using the pipette method to determine particle size (Carter and Gregorich 2008) and classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).

Appendix L.2a Soil characteristics for the Kelburn Farm, located near St. Adolphe, in spring 2015 prior to planting corn test crop						
Texture	Particle Distribution			Soil Test[a]		
	Sand	Silt	Clay	P	Zn	pH
	——— $g\ kg^{-1}$ ———			——— $mg\ kg^{-1}$ ———		
Clay	31	29	40	41(VH+)[b]	2.3	6.9

[a] Concentrations at 0-15 cm depth; P, Olsen-bicarbonate; Zn, DTPA-Zn; pH, soil pH 1:1 soil/water.

[b] Level of agronomic P sufficiency in soil indicated by the letters VH means very high (MAFRD 2007).

Appendix L.3. Preceding Crop Management and Site Preparation

In the spring of 2014 canola and soybean were grown as preceding crops. Roundup Ready® canola (Dekalb 73-75 RR) variety was seeded at 100 plants m^{-2} at 13-25 mm depth and Roundup Ready® soybean (Dekalb 24-10 RY RR) variety was planted at 50 plants m^{-2} at 25 mm depth by the Plant Science Department, University of Manitoba. Prior to planting, soybean seed was treated with Cruiser Maxx Vibrance® seed treatment and granular inoculant was applied in-furrow at a rate of 22 kg ha^{-1}. Recommended herbicides for weed control in canola and soybean crops were applied using a tractor sprayer. Samples of the canola and soybean grain were collected for yield determination on 2014 Sep. 24 and 2014 Oct. 10, respectively. The producer harvested the remainder of the crop and plots were tilled in the fall, using a tandem disk to anchor canola and soybean crop residue in their respective blocks.

Appendix L.4. Experimental Design and Treatments

The experimental design was a randomized split-block design with four replicates, with the preceding crops of canola and soybean forming blocks that were subdivided for the starter fertilizer treatments. The starter fertilizer treatments consisted of a control (no starter) and two rates of 30 and 60 kg P_2O_5 ha^{-1} in the form of MicroEssentials® SZ (MESZn, 12-40-0-10-1) side banded (SB) (5 cm to the side and 2.5 cm below the seed) during corn planting in the spring.

Although the number of treatments was limited at St. Adolphe, the available corn planting equipment allowed for a total of 12 to 16 replicates of these treatments to be planted and harvested. The treatments are summarized as follows:

1. Control (no starter)
2. 30 kg P_2O_5 and 7.5 kg S and 0.75 kg Zn ha^{-1} MESZn SB
3. 60 kg P_2O_5 and 15 kg S and 1.5 kg Zn ha^{-1} MESZn SB

Appendix L.4a Number of replicates of each treatment planted and harvest at St. Adolphe in 2015

Treatment					Treatment Replicates
Preceding Crop	Fertilizer Treatment			Products[a]	
	P_2O_5	S	Zn		
	kg ha^{-1}				number of replicates
Canola	0	0	0	Control (no starter)	16
	30	7.5	0.75	MESZn	12
	60	15	1.5	MESZn	12
Soybean	0	0	0	Control (no starter)	16
	30	7.5	0.75	MESZn	12
	60	15	1.5	MESZn	12

[a] MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).

Nitrogen fertilizer was broadcast in the spring as SUPERU® prior to corn planting and incorporated with the corn planter. Sufficient N was applied to each plot to reach a target N supply of 250 kg N ha^{-1}, taking into account N in the starter fertilizer treatments and soil-N concentrations. Corn hybrid Dekalb 26-28RIB Genuity® VTDoublePRO® (76-d RM) was planted 40-45 mm deep at 80,942 seeds ha^{-1} in 76-cm-wide rows using a four-row planter (John Deere 7000 4R drawn planter) at a speed of 3.2 km hr^{-1} on 2015 June 01. The corn hybrid was chosen based on corn heat units and growing conditions of the study area, but also needed to represent a hybrid that was commonly grown by Manitoba corn growers. Each two-row plot measured 1.5 by 10 m. Appropriate herbicides were applied in the crop with a tractor sprayer by on site farm operators.

Appendix L.5. Weather Conditions

Accumulated corn heat units (CHU) were sufficient at St. Adolphe for the corn hybrid to reach physiological maturity (2150 CHU) (Table L.5a). Total recorded growing season precipitation was below the required amount by the crop, considering a 7519 kg ha^{-1} corn crop uses about 530 mm in an average year, with corn water-use being the greatest during reproductive phases of silking and pollination (July-Aug.) (Manitoba Corn Growers Association 2014).

Table L.5a Maximum, minimum and average air temperature, corn heat units (CHU), monthly and total precipitation, during the 2015 growing season at St. Adolphe

Air Temperature[a]				Precipitation					
T_{max}	T_{min}	$T_{average}$	CHU_{total}	June	July	Aug.	Sep.	Oct.	Total
air temperature, C°				mm					
23.6	10.0	16.8	2799[a]	83.2	129.0	69.8	69.1	29.4	380.5[a]

[a] Weather data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for St. Adolphe 2015 from 2015 June 01-Oct.26.

Appendix L.6. Early Season Crop Measurements

Plant stand was counted at 4 wk after planting to assess final plant stand populations. The number of emerged plants was determined in the two rows from a 4-m in length in each row, for a total 8-m length per plot.

Appendix L.7. Late Season Crop Measurements

Grain yield and moisture content were determined by harvesting two, 4-m long rows from each plot using a plot combine (Wintersteiger Classic with HarvestMaster® Classic GrainGage system). Grain yields were adjusted to 155 g kg^{-1} moisture.

Appendix L.8. Statistical Analysis

Glimmix Procedure in SAS 9.4 was used for statistical analyses (SAS Institute, Inc. 2016). Fertilizer treatment was considered a fixed effect and block and crop × block were considered random effects. Conformity of the data was tested using the Shapiro-Wilk Statistic and assumptions regarding data conformity were tested using Proc Univariate. The Tukey-Kramer test was used to assign letter groupings for treatment least squares means (P<0.05).

Appendix L.9. Results and Discussion

Both starter fertilizer treatments decreased grain moisture at harvest by an average of 1.2 g kg^{-1} in corn after canola, relative to its respective unfertilized control and not in fertilized corn after soybean (Table L.9a). However, both rates of MESZn had the same moisture at harvest, regardless of the preceding crop. Therefore, the grain moisture response to starter fertilizer for each preceding crop was largely influenced by the unfertilized controls. However, grain moisture at harvest was not significantly different between the unfertilized corn after canola and corn after soybean controls. A small reduction in grain moisture at harvest, such as the one observed at St. Adolphe in 2015 can help reduce drying costs and as a result, potentially cover the cost of starter fertilizer if corn is planted after canola.

Both rates of MESZn increased grain yield at harvest by an average of 1741 kg ha^{-1}, relative to the unfertilized control (Table L.9a). Placement of starter fertilizer in close proximity to the seed provided adequate nutrition to the corn crop and the response to starter fertilizer was similar, regardless of the preceding crop.

Although the STP concentration at St. Adolphe was very high, a substantial response to starter fertilizer was still observed. This is contrary to studies where the likelihood of starter fertilizer response was reportedly greater on soils with low STP concentrations compared with soils where STP concentrations were medium to high (Bermudez and Mallarino 2002). However, since we did not assess early and mid season response to starter fertilizer in this experiment, it is difficult to explain other factors that may have contributed to this unlikely grain yield response. It is uncertain whether early season growth contributed to these treatment differences or whether it was fertilizer nutrient composition, or both. Therefore, due to the unexpected yield response to starter fertilizer at this high soil fertility site, another experiment was set up in 2016 to evaluate early, mid and late season corn response to side banded phosphorus, zinc and sulphur starter fertilizers.

Table L.9a Grain moisture and grain yield at harvest: effect of preceding crop and starter fertilizer applied in a 5 cm x 2.5 cm spring side band at St. Adolphe in 2015

Treatment					Crop Measurement[a]	
Preceding Crop	Fertilizer Treatment			Products[b]	Grain Moisture	Grain Yield
	P_2O_5	S	Zn			(adjusted to 155 g kg^{-1} moisture)
	kg ha^{-1}				g kg^{-1}	kg ha^{-1}
Canola	0	0	0	Control (no starter)	20.8*a*[c]	7105
	30	7.5	0.75	MESZn	19.7*bc*	8933
	60	15	1.5	MESZn	19.5*c*	9191
Soybean	0	0	0	Control (no starter)	20.4*ab*	7911
	30	7.5	0.75	MESZn	19.8*bc*	9189
	60	15	1.5	MESZn	19.9*abc*	9681
Canola					20.0	8409
Soybean					20.0	8927
	0	0	0	Control (no starter)	20.6	7508*b*
	30	7.5	0.75	MESZn	19.7	9061*a*
	60	15	1.5	MESZn	19.7	9436*a*

ANOVA	Df	Pr>F	
Fert	2	<.0001*	<.0001*
Crop	1	0.9598	0.1101
Crop*Fert	2	0.0392*	0.5705
Coeff Var (C.V.)		4	16

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-c Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
[*] Significant at $P < 0.05$.

Appendix M

Mosaic MicroEssentials® SZ Study: Kelburn Farm, St. Adolphe, Manitoba (2016)

Appendix M.1. Background and Objectives

A second experiment was set up at the Kelburn Farm, near St. Adolphe in 2016 to follow up on the first experiment at this site. Quarantine regulations imposed by Canadian Food Inspection Agency (CFIA) were lifted in 2016 and we were able to perform most field activities. In 2016, we modified the fertilizer treatments from the first year of this study to accommodate more products. Since there were no yield differences between the low and high rate of MicroEssentials® SZ in 2015, only the low rate was used in 2016. The objectives of the study were to evaluate early, mid and late season corn response to phosphorus, zinc and sulphur fertilizer applied as a side banded starter.

Appendix M.2. Site Description and Characteristics

The experiment site was located at the Kelburn Farm near St. Adolphe (49°41' N, 97° 7' W), where Olsen extractable soil test P concentration was 35 mg kg^{-1} (Table M.2a). The high soil test P concentration was expected, considering that Kelburn Farm produced beef cattle in the past and some soils at the Farm were heavily manured during that period. Prior to corn planting, 10 random soil samples were collected in the spring (0-15 and 15-60 cm depths) to determine basal rates of any additional nutrients, including potassium (K), micronutrients other than zinc (Zn) and to measure residual nitrate-N and determine nitrogen (N) fertilizer requirements. Soil samples were sent to AgVise Laboratories (Northwood, ND, USA). Soil texture was determined using the pipette method to determine particle size (Carter and Gregorich 2008) and classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998).

Table M.2a Soil characteristics for the Kelburn Farm near St. Adolphe, in spring 2016 prior to planting corn test crop

Texture	Particle Distribution			Soil Test			
	Sand	Silt	Clay	P[a]	Zn[a]	S	pH
	g kg^{-1}			mg kg^{-1}		kg ha^{-1}	
Clay	17	29	55	35(VH+)[b]	2.6	29[c] 114[d]	7.0

[a] Concentrations at 0-15 cm depth; P, Olsen-bicarbonate; Zn, DTPA-Zn; pH, soil pH 1:1 soil/water.
[b] Level of agronomic P sufficiency in soil indicated by the letters VH means very high (MAFRD 2007).
[c] Concentrations at 0-15 cm depth; S, turbidometric method.
[d] Concentrations at 15-60 cm depth; S, turbidometric method.

Appendix M.3. Preceding Crop Management and Site Preparation

In the spring of 2015, the first phase of the experiment was a uniform soybean production, where grain was harvested and straw was left on the field according to the production practices at the station. The soil was tilled in the fall following soybean harvest.

Appendix M.4. Experimental Design and Treatments

The experimental design was a randomized complete-block design with eight replicates. The starter fertilizer treatments consisted of a control (no starter) and low rate of 30 kg P_2O_5 in the form of MicroEssentials® SZ (MESZn, 12-40-0-10-1), monoammonium phosphate (MAP, 11-52-0) alone and MAP plus ammonium sulphate (AS, 21-0-0-24). Sulphur was added with the MAP+AS and MESZn treatments at a rate of 7.5 kg S ha^{-1}. Zinc was added with the MESZn treatment at a rate of 0.75 kg Zn ha^{-1}. All fertilizer treatments were side banded (SB) (5 cm to the side and 2.5 cm below the seed) during corn planting in the spring. The treatments are summarized as follows:

T1) Control (no starter)		
T2) 30 kg $P_2O_5^{-1}$	MAP	SB
T3) 30 kg P_2O_5 and 7.5 kg S ha^{-1}	MAP+AS	SB
T4) 30 kg P_2O_5 and 7.5 kg S and 0.75 kg Zn ha^{-1}	MESZn	SB

Nitrogen fertilizer was broadcasted in the spring as AGROTAIN® treated urea prior to corn planting and incorporated with the corn planter. Sufficient N was applied to each plot to reach a target N supply of 250 kg N ha^{-1}, taking into account N in the starter fertilizer treatments and soil-N concentrations. Corn hybrid Dekalb 26-28RIB Genuity® VTDoublePRO® (76-d RM) was planted 40-45 mm deep at 80,942 seeds ha^{-1} in 76-cm-wide rows using a four-row planter (John Deere 1755 4R drawn planter) at a speed of 3.2 km hr^{-1} on 2016 May 13. The corn hybrid was chosen based on corn heat units and growing conditions of the study area, but also needed to represent a hybrid that was commonly grown by Manitoba corn growers. Each four-row plot measured 3 by 8 m. Appropriate herbicides were applied in the crop with a bike sprayer up to V4 growth stage and a backpack sprayer for the subsequent crop growth stages.

Appendix M.5. Weather Conditions

Accumulated corn heat units (CHU) at St. Adolphe were sufficient for the corn hybrid to reach physiological maturity (2150 CHU) (Table M.5a). Total recorded growing season precipitation was below the required amount by the crop, considering a 7519 kg ha^{-1} corn crop uses about 530 mm in an average year, with corn water-use being the highest during reproductive phases of silking and pollination (July-Aug.) (Manitoba Corn Growers Association 2014).

Table M.5a Maximum, minimum and average air temperature, corn heat units (CHU), monthly and total precipitation, during the 2016 growing season at St. Adolphe

Air Temperature[a]				Precipitation					
T_{max}	T_{min}	$T_{average}$	CHU_{total}	May	June	July	Aug.	Sep.	Total
air temperature, C°				mm					
23.4	10.8	17.1	2980[a]	57.3	90.6	59.3	120.9	71.9	420.0[a]

[a] Weather data recorded from Manitoba Agriculture Daily Weather Report (http://tgs.gov.mb.ca/climate/dailyreport.aspx) for St. Adolphe 2016 from 2016 May 13-Oct.11.

Appendix M.6. Early Season Crop Measurements

Plant stand was counted at 4 wk after planting to assess final plant stand populations. The number of emerged plants was determined in two middle rows of each plot, each being 4 m in length for a total 8-m length per plot.

Early season biomass was collected by cutting 10 randomly selected plants at ground level from the two outside rows from each plot at V4 (based on visible leaf collar). Fresh samples were weighed and air-dried for a week. Biomass was then cut into smaller sections, oven dried at 60°C for 72 h, weighed, and ground to pass through a 1-mm screen.

Phosphorus, zinc and sulphur concentration in plant tissue and uptake were determined for early season biomass collected at V4. Dried and ground samples were sent to AgVise Laboratories (Northwood, ND, USA) for P, Zn and S analysis. Plant P and Zn uptake were calculated from nutrient concentrations and oven-dried early season biomass weights.

Appendix M.7. Mid to Late Season Crop Measurements

In-season cob moisture was assessed weekly, starting at dough (R4) stage until approximately one week prior to harvest. Moisture was measured using an Electrophysics® moisture meter with corn probe (Dutton, Ontario Model MT808C). Two readings were taken per cob, from six randomly selected cobs per plot. Final moisture reading was an average of 12 readings for each plot.

Appendix M.8. Late Season Crop Measurements

Due to black bird damage at St. Adolphe in 2016, grain yield and moisture content were determined by hand-harvesting 32 corn cobs from each plot and stationary threshing with a plot combine (Wintersteiger Classic with HarvestMaster® Classic GrainGage system). Corn cobs were collected from consecutive plants where corn socks were used in order to protect them from bird damage. Corn cobs were hand-harvested from each plot from an area equivalent to 4.05 m^2 (1/1000 of an acre) determined from plant stand counts at 4 wk following planting. Grain yields were adjusted to 155 g kg^{-1} moisture.

Appendix M.9. Statistical Analysis

Glimmix Procedure in SAS 9.4 was used for statistical analyses (SAS Institute, Inc. 2016). Fertilizer treatment was considered a fixed effect and block was considered a random effect. Conformity of the data was tested using the Shapiro-Wilk Statistic and assumptions regarding data conformity were tested using Proc Univariate. The Tukey-Kramer test was used to assign letter groupings for treatment least squares means (P<0.05).

Appendix M.10. Results and Discussion

Early season biomass at V4 was greater by an average of 23% with MAP and MAP+AS treatments, compared to the unfertilized control (Table M.10b). However, there was no difference in early season biomass among any of the fertilized treatments.

Phosphorus concentration and uptake were greater by an average of 10 and 35% with MAP and MAP+AS treatments, respectively compared to the unfertilized control (Table M.10a). Further, S uptake was also greater with MAP and MAP+AS treatments compared to the unfertilized control. However, there were no differences in P concentrations, and P and S uptake among any of the fertilized treatments. Relative to the control, MESZn composition could have affected S uptake in the fertilized treatments since only 50% of the S is in the available form and the other 50% is in elemental, not readily available form. However, S concentrations in plant tissue were not affected; therefore, the differences in S uptake may have also been driven by differences in early season biomass. Further, Zn concentrations and uptake in the fertilized treatments were not different from the unfertilized control.

Significant differences in moisture at harvest were measured only between the MAP+AS and MESZn treatments, where the MESZn treatment reduced grain moisture by 0.56 g kg^{-1} (Table M.10b). Grain moisture at harvest in the unfertilized control (26.05 g kg^{-1}) was not significantly different from any of the fertilized treatments.

Grain yields were very high in the unfertilized control (13279 kg ha^{-1}) and starter fertilizer did not increase grain yields at St. Adolphe in 2016 (Table M.10b). Overall, P concentrations obtained in our experiment (3.4 to 4.5 g kg^{-1}) at the V4 stage should have been sufficient to obtain desired yields. Further, P, Zn and S soil concentrations were adequate according to Manitoba levels of agronomic sufficiency. Therefore, the likelihood of response to starter fertilizer was low at this site and the lack of response measured in 2016 was probably more typical for this soil than the substantial response measured in 2015.

Table M.10a Early season P, Zn and S uptake by corn at V4: effect of starter fertilizer applied in a 5 cm x 2.5 cm spring side band at St. Adolphe in 2016

Treatment					Early Season Concentrations and Uptake of P, Zn, and S[a]					
Fertilizer Treatment			Products[b]		Phosphorus		Zinc		Sulphur	
P_2O_5	S	Zn			Concentration	Uptake	Concentration	Uptake	Concentration	Uptake
kg ha^{-1}					g kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}×10^{-2}	g kg^{-1}	kg ha^{-1}
0	0	0	Control (no starter)		4.1*b*[c]	1.1*b*	35	1.0	2.5	0.7*b*
30	0	0	MAP		4.5*a*	1.5*a*	33	1.1	2.6	0.9*a*
30	7.5	0	MAP + AS		4.5*a*	1.5*a*	32	1.1	2.7	0.9*a*
30	7.5	0.75	MESZn		4.4*ab*	1.4*ab*	31	1.0	2.5	0.8*ab*
ANOVA				Df	Pr>F					
Fert				3	0.0108*	0.0025*	0.1315	0.3466	0.0982	0.0033*
Coeff Var (C.V.)					8	19	12	20	8	19

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
* Significant at $P< 0.05$.

Table M.10b Early season biomass at V4, grain moisture and grain yield at harvest: effect of starter fertilizer applied in a 5 cm x 2.5 cm spring side band at St. Adolphe in 2016

Treatment					Crop Measurements[a]		
Fertilizer Treatment			Products[b]		Early Season Biomass	Moisture at Harvest	Grain Yield
P_2O_5	S	Zn					
kg ha^{-1}					kg ha^{-1}	g kg^{-1}	kg ha^{-1}
0	0	0	Control (no starter)		274*b*[c]	26.05*ab*	13279
30	0	0	MAP		336*a*	26.06*ab*	13155
30	7.5	0	MAP + AS		334*a*	26.56*a*	13127
30	7.5	0.75	MESZn		315*ab*	26.00*b*	13077
ANOVA				Df	Pr>F		
Fert				3	0.0146*	0.0346*	0.6283
Coeff Var (C.V.)					14	2	2

[a] Least square means (LSmeans) recorded from Proc Glimmix.
[b] Monoammonium Phosphate (MAP, 11-52-0-0); Ammonium Sulphate (AS, 21-0-0-24); MicroEssentials SZ (MESZn, 12-40-0-10-1Zn).
[c] a-b Least square mean values followed by the same lower case letter (within columns) are not significantly different, determined by Tukey-Kramer grouping.
* Significant at $P< 0.05$.