Corn Hybrid Response to Starter Fertilizer

by

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ABSTRACT

Two studies were conducted, first to assess differential response of corn hybrids to starter fertilizer in terms of early plant growth, maturity, phosphorus (P) uptake, grain moisture, grain yield and second, to assess rooting differences between hybrids determined to be either responsive or non-responsive to starter fertilizer. The first study consisted of a field experiment to evaluate corn response to starter nitrogen (N) plus P and starter P alone. The starter N plus P experiment was conducted in 2017 and 2019 with starter fertilizer treatments of no in-furrow fertilizer and 22 kg P_2O_5 ha^{-1} plus 6.7 kg N ha^{-1} applied in-furrow. The experiment to evaluate starter P alone was conducted in 2018 and 2019 with starter fertilizer treatments of 22 kg P_2O_5 ha^{-1} plus 6.7 kg N ha^{-1} applied in-furrow or 6.7 kg N ha^{-1} dribble banded pre-emergence to match the rate of N applied in the in-furrow treatment. Each experiment was conducted at eight site-years, each with eight hybrids. Both starter treatments, starter N plus P and starter P alone, resulted in an overall increase in grain yield. However, when responses were analyzed for individual hybrids, the increase in grain yield due to starter N plus P or starter P alone was significant for DKC26-28RIB, but not the other seven hybrids. Differential response in grain moisture was observed at one site-year where grain moisture at harvest with starter P alone was lower for DKC26-28RIB, but higher for DKC33-78RIB, compared to no starter. Hybrids did not differ in early season biomass, P uptake, days required to reach silking, or plant height response to starter N plus P or P alone.

In the second study, early seedling root length and root surface area of hybrids were measured and evaluated for their relationship with response to starter N plus P and P alone from the field experiments. Eight hybrids were grown in germination pouches for 11 days at 11.5/8.5°C (16hr/8hr) without light or supplemental nutrients. Digital images were captured and analyzed to

measure root length and surface area. At 11 days, root length and surface area were related to percent increase in grain yield due to starter N plus P, with R^2 values of 0.68 and 0.67, respectively. However, root length and surface area were not related to percent grain yield increase due to starter P alone. Furthermore, root length and surface area were not related to percent increase in early season biomass, P uptake, days to silking, plant height, or grain moisture at harvest due to starter N plus P or P alone.

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FOREWORD

This thesis has been prepared following the guidelines of the Department of Soil Science at the University of Manitoba. Manuscripts follow the style outlined by the Canadian Journal of Soil Science. This thesis includes a general introduction of literature, a manuscript for the field experiments evaluating corn hybrid response to starter fertilizers, and a manuscript for the controlled environment study evaluating the relationship between seedling root measurements and response to starter fertilizer. The synthesis, list of references and appendices follow the manuscripts.

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1. INTRODUCTION

Nitrogen (N) and phosphorus (P) are two of fourteen essential mineral nutrients required for normal plant growth. Nitrogen is often the most deficient nutrient for crop production and is a key component of organic compounds such as amino acids, nucleic acids, adenosine triphosphate (ATP) and chlorophyll, and is responsible for many biochemical reactions (Havlin et al. 2004). Phosphorus is a critical component of nucleic acids, ATP, and phospholipids, thus responsible for a variety of plant functions including cell structure, energy transfer and storage, growth and reproduction (Havlin et al. 2004). When N or P is deficient, reductions in growth, development, and yield can occur. In corn (*Zea mays* L.), N and P deficiencies can be identified by yellowing of older leaves (Havlin et al. 2004) and purpling of leaves at the three to five leaf-collar stage (V3-V5) (Cobbina and Miller 1987; Havlin et al. 2004), respectively.

Plant roots are responsible for anchoring the plant in the soil and the acquisition of water and nutrients (Mengel and Barber 1974; Feldman 1994). The corn root system is comprised of seminal and nodal roots. Seminal roots, originating from the seed, are the first roots to emerge and are important for early season water and nutrient uptake as well as seedling vigour (Hochholdinger et al. 2018; Nielsen 2020). Nodal roots are shoot-borne roots that comprise most of the root system in mature plants (Hochholdinger et al. 2004). Further, lateral roots branch off both seminal and nodal roots, providing greater surface to volume ratio for increased water and nutrient uptake (Yu et al. 2019). In addition, outgrowths of epidermal cells called root hairs increase surface area to better acquire nutrients (Clarkson 1985; Zhu et al. 2010).

Nutrient uptake depends not only on the roots themselves, but also the availability of nutrients at the root surface (Mackay and Barber 1984), which differs from one nutrient to another, based on mobility. Phosphorus in the phosphate form is relatively immobile, moving by diffusion as little as 0.5 mm in soil (Grant et al. 2001). Nitrogen when present as nitrate is more mobile as it can move with soil water via mass flow (Havlin et al. 2004). However, the availability of both N and P may be especially limited early in the growing season due to slow rates of mineralization, solubility, and diffusion under cool soil temperatures (Cassman and Munns 1980; Mackay and Barber 1984; Sheppard and Racz 1984). In addition, cold temperatures can reduce root branching and growth, limiting the plant's ability to take up nutrients (Mackay and Barber 1984; Kasper and Bland 1992; Chassot and Richner 2002). Due to the importance of N and P and the potential of insufficient early season availability, placing nutrients close to seed may be beneficial.

The use of starter fertilizer (SF) in corn production is common. Starter fertilizer can be side-banded near the seed (typically 5 cm to the side and 5 cm below the seed) or directly in-furrow (IF), providing nutrients to the seedling in a positional availability form (Bermudez and Mallarino 2004; Kaiser et al. 2016). Banding fertilizer beside the seed requires more complex equipment, but allows for greater rates of nutrient to be applied safely compared to IF applications (Roth et al. 2006; Kaiser et al. 2016). Starter fertilizer placed with the seed enables higher rates of absorption, especially for immobile nutrients such a P (Miller et al. 1971), but can result in reduced stand count and yield if applied at high rates, due to ammonia toxicity or salt injury (Rehm and Lamb 2009). However, corn is relatively tolerant to some IF fertilizers, such as ammonium polyphosphate (APP). Kaiser and Rubin (2013) determined that seed-placed APP is safe up to 32 kg ha^{-1} on sandy loam soils and 73 kg ha^{-1} on loam. Regardless of method, applying fertilizer close to the seed can increase nutrient use efficiency (Jokela 1992; Kaiser et al. 2005; Grant and Flaten 2019).

Starter fertilizer can increase early growth, advance development, decrease grain moisture, and increase grain yield of corn (Bundy and Andraski 1999). Increases in early-season growth are often large with starter fertilizers containing N plus P (Lauzon and Miller 1997; Bermudez and Mallarino 2004). In Manitoba where soils are cool, 85-110% increases in early-season growth with starter P have been recorded (Rogalsky 2017). In addition to increased early growth, starter fertilizers containing N plus P can hasten the rate of corn development measured as decreases in the days to silking (Cromley et al. 2006; Bundy and Andraski 1999; Kaiser et al. 2016), appearance of black layer (Bullock et al. 1993), and grain moisture at harvest (Bundy and Andraski 1999; Mascagni and Boquet 1996; Kaiser et al. 2016).

Although SF often increases early season-growth and development, grain yield responses are often less frequent and of lower magnitude than early season responses (Vetsch and Randal 2002; Kaiser et al. 2005). Bermudez and Mallarino (2002) found early growth increases (32%) were poorly correlated with grain yield increases (2.4%) due to starter N plus P. Bermudez and Mallarino (2004) observed a yield response in three out of seven sites with starter N plus P, with an across-site yield increase of 1.1%, while other research showed no grain yield increase with starter N plus P application (Bullock et al. 1993; Kaiser et al. 2016) or starter N plus P plus potassium (K) (Roth et al. 2006; Rehm and Lamb 2009). The lack of yield increase could be due to SF not increasing the period of grain fill or final plant size (Bullock et al. 1993).

Crop response to SF can also be impacted by management and environmental factors. Cooler soil temperatures at planting favour phenotypic responses to SF due to reduced root growth and limited nutrient mobility (Kaspar and Bland 1992; Randall and Hoeft 1988). Bundy and Andraski (1999) found that starter N plus P plus K resulted in a greater probability of grain yield increase when planting was delayed, particularly for later relative maturity (RM) hybrids due to a greater realization of yield potential before a killing frost. However, Kaiser et al. (2016) found that neither planting date, nor hybrid RM affected response to starter N plus P. Response to starter fertilizers containing N plus P can be more frequent on soils testing low in P (Wortmann et al. 2006). Using precision agriculture tools (yield monitors, intensive soil sampling, geographical information systems), Bermudez and Mallarino (2002) found yield response to starter fertilizer containing N plus P between and within fields were larger when soil test P (STP) concentrations were below optimum. However, increases in grain yields have been observed on soils with high STP concentration due to increased positional availability of immobile nutrients and benefits from nutrients other than P in the starter blend (Lauzon and Miller 1997; Mascagni and Boquet 1996; Bundy and Andraski 1999; Bermudez and Mallarino 2002). In terms of early growth response, studies have suggested that increased P availability near the seed can increase early-season biomass independently of STP concentrations (Randall and Hoeft 1988; Mallarino et al. 1999; Bermudez and Mallarino 2002; Roth et al. 2006).

Since starter fertilizers usually contain two or more nutrients, it can be difficult to identify which specific nutrient is contributing to an increase in grain yield (Kaiser et al. 2005; Mallarino et al. 2011). Also, the P fertilizer requirement and response of crops can be affected by rotational decisions that impact arbuscular mycorrhizal fungi (AMF) colonization (Plenchette and Morel 1996). Crops such as corn and soybean host AMF which increase P accessibility compared to canola, a non-mycorrhizal host (Plenchette and Morel 1996; Bittman et al. 2004). In a crop rotation study, starter P reduced grain moisture at harvest when corn followed canola, but not when following soybean (Rogalsky 2017).

In addition to environmental and management factors, SF response may differ between corn hybrids. In Florida, Teare and Wright (1990) evaluated 21 hybrids and reported that although starter N plus P increased grain yield when averaged across hybrids compared to no starter, the hybrid by starter interaction indicated that eight hybrids had a positive grain yield increase whereas 13 hybrids had negative or no grain yield increases from starter N plus P. In Kansas, Gordon et al. (1997) evaluated the response of five hybrids to starter N plus P and Gordon and Pierzynski (2006) evaluated the response of four hybrids to SF combinations containing N, P, K, sulphur and zinc. In both experiments, starter fertilizers containing N plus P increased early-season biomass and uptake of N and P of all hybrids. However, starter N plus P consistently reduced thermal units needed to reach silking, increased total P uptake (grain plus stover), and increased grain yield of three hybrids, but not the other two in the experiment by Gordon et al. (1997). Similarly, Gordon and Pierzynski (2006) reported that starter fertilizers containing N plus P reduced thermal units needed to reach silking, increased total P uptake, increased grain yield, and reduced grain moisture at harvest for two out of four hybrids. In contrast, other studies reported that when a grain yield response occurred as a result of starter N plus P, all hybrids responded similarly (Mascagni and Boquet 1996; Buah et al. 1999). Where hybrid differences are reported, responsiveness to SF has been attributed to morphological and physiological differences in root characteristics (Gordon et al. 1997; Gordon and Pierzynski. 2006).

Corn genotypes differ in root characteristics which can influence the amount of nutrients absorbed (Mackay and Barber 1984; Pan et al. 1985; Gordon et al. 1997). Nielsen and Barber (1978) evaluated 12 inbred lines and reported a three-fold variation in root weight between inbreds at 16 days after planting. Differences can also be observed at later growth stages, as Costa et al. (2002) reported a three-fold difference in root length and surface area between hybrids at the silking stage. Root morphology and rate of growth can also be influenced by temperature (Kasper and Bland 1992; Costa et al. 2002). Length, surface area, weight, volume, and rate of growth of corn roots are less at cold than warm soil temperatures (Mackay and Barber 1984; Chassot and Richner 2002; Wijewardana et al. 2015). However, corn genotypes can differ in cold tolerance (Hund et al. 2007; Hund et al. 2008). Wijewardana et al. (2015) reported genetic variation in root parameters (including length, volume, length per volume, surface area, dry weight and diameter) among 33 commercial hybrids when evaluated at three temperature regimes. Wijewardana et al. (2015) was able to classify hybrids by cold tolerance based on the ability to continue root growth at low temperatures. The ability of certain hybrids to continue root growth despite cool temperatures, allows for greater soil exploration and nutrient supply (Hund et al. 2007; Hund et al. 2008; Wijewardana et al. 2015) which may influence responsiveness to starter fertilizer (Gordon and Pierzynski 2006).

In a field experiment, Gordon and Pierzynski (2006) measured root growth at V6 using soil cores and found that hybrids with no yield response to starter N plus P (Pioneer 3563 and DeKalb 646) had greater early-season root growth when no starter N plus P was applied, compared to yield-responsive hybrids (Pioneer 3346 and DeKalb 591). Starter N plus P increased root count and depth at the six-leaf stage of Pioneer 3346 and DeKalb 591, but had no effect on root growth of Pioneer 3563 and DeKalb 646. In two glasshouse experiments, Rhoads and Wright (1998) reported greater root weight and greater P uptake and N uptake at 33-41 days after planting for a hybrid that was previously determined to be non-responsive to starter N plus P compared to a responsive hybrid.

Several methodologies have been developed to study root growth. The choice of method depends upon the aim of the research. Bohm (1979) lists the advantages and disadvantages of various methods for studying roots including excavation, indirect and container methods.

Excavation is a common method for studying root growth in the field environment as it allows for the collection of the entire root system from its natural environment (Bohm 1979). However, excavation can be time consuming, requires large amounts of labour, and is disruptive to the plant which does not allow for continued study of the root (Bohm 1979). Indirect methods are used when the research aims to study root activity rather than the physical amount of roots in the soil (Bohm 1979). Radioactive tracers are injected into the soil which when taken up by plants, provide an indirect measure of root activity (Bohm 1979). Container methods allow for the study of roots in a chosen medium within a controlled environment. Root container methods allow for easier handling then field methods and the ability to control environmental variability (Bohm 1979). However, the duration of the experiment can be limited by the container. If the root system becomes too large, it will be restricted by the container and may not represent rooting characteristics in the field.

In Manitoba, acres planted to corn are growing due to increased interest by growers, development of new hybrids and greater understanding of beneficial management practices for corn (Manitoba Corn Growers Association 2018). Although the effects of SF in corn production have been studied extensively, the differential growth response of hybrids to SF has not, especially for hybrids grown in the Northern Great Plains, where the growing season is short and soils at planting are generally cold. Since the growth and profitability of corn production in Manitoba depend on selecting hybrids and agronomic practices that are appropriate for this region, the objectives of the field experiments were to evaluate the effects of starter N plus P and P alone on the growth, nutrient uptake, development and grain yield of eight commercially available hybrids. We hypothesized that response to both starter N plus P and P alone would differ among hybrids. The objectives of the controlled environment study were to evaluate early seedling root length and surface area of the different hybrids and determine if there is a relationship between early root growth and phenotypic response to starter N plus P or P alone. We hypothesized that hybrids will differ in root measurements and that hybrids with greater root length and root surface area will have smaller phenotypic response to starter N plus P and P alone.

2. Corn Hybrid Response to Starter Nitrogen Plus Phosphorus and Phosphorus Alone

2.1 Abstract

Starter fertilizer application in corn (*Zea mays* L.) production can be especially beneficial in Manitoba due to cold soils at planting and a short growing season. However, previous studies elsewhere have shown starter fertilizer to be beneficial for certain hybrids and not others. The objectives of this study were to assess the variability in early growth, maturity, grain moisture, and grain yield response of corn hybrids suited for Manitoba to starter N plus P and starter P alone. The starter N plus P experiment was conducted in 2017 and 2019 at eight locations in Manitoba with eight hybrids and two starter fertilizer treatments of either no in-furrow fertilizer or 22 kg P_2O_5 ha^{-1} plus 6.7 kg N ha^{-1} applied in-furrow. The experiment to evaluate starter P alone was conducted in 2018 and 2019 at eight locations in Manitoba with eight hybrids and two starter fertilizer treatments of either 22 kg P_2O_5 ha^{-1} plus 6.7 kg N ha^{-1} applied in-furrow or no in-furrow P, but 6.7 kg N ha^{-1} dribble banded pre-emergence. The dribble banded N in the second treatment was applied to match the rate of N applied in the in-furrow starter treatment. Overall, starter fertilizer increased grain yields in both experiments. However, hybrids differed in grain yield and grain moisture response to starter fertilizer. When fertilizer responses were analyzed for individual hybrids, both starter N plus P and starter P alone increased grain yield of DKC26-28RIB, but not the other seven hybrids. Hybrids differed in grain moisture response to starter P alone at one site-year where grain moisture at harvest was lower for DKC26-28RIB and higher for DKC33-78RIB. Starter N plus P increased early season biomass, P concentration, and P uptake of all hybrids evaluated. Both starter N plus P and P alone decreased time required to reach silking across all hybrids. Results from this study show that these corn hybrids responded

similarly to starter fertilizer early in the season, but the effect of starter fertilizer on grain yields varied from one hybrid to another.

2.2 Introduction

In 2019, corn (*Zea mays* L.) was the fifth most planted crop in Canada, with farmers reporting 1.49 million hectares planted (Statistics Canada 2020). The area planted to corn has steadily risen, especially in Western Canada where between 2011 and 2019, reported corn acreage has increased 142% (Statistics Canada 2020). In Western Canada, including Manitoba, corn production is limited by cool temperatures and a short growing season (Nadler and Bullock 2004). Thus, selection of corn hybrids and proper timing of planting must be considered carefully. However, timely planting often means planting into cool soils which may limit root growth and nutrient availability (Gordon and Pierzynski 2006; Grant and Flaten 2019). With the challenges of cold soils at planting and a short growing season, application of starter fertilizer (SF) may benefit corn production in this region.

Nitrogen (N) and phosphorus (P) are essential nutrients required for normal plant growth. Nitrogen and phosphorus are key components of nucleic acids and adenosine triphosphate, thus critical for many plant functions including energy storage and transfer, protein production, photosynthesis, growth, and reproduction (Havlin et al. 2004). Symptoms of P deficiency in corn can include purpling of leaves early at the three to six leaf-collar stage (V3-V6), slower maturation, and reduced grain yield later in the season (Cobbina and Miller 1987; Havlin et al. 2004). Nitrogen deficiency symptoms in young plants appear as yellowing of the older leaves and, if not corrected, can lead to stunting of growth and a reduction in grain yield (Havlin et al. 2004). In terms of behaviour in soils, N present in the nitrate form can move with soil water via mass flow, whereas P movement by diffusion is very limited (Havlin et al. 2004; Grant et al. 2001). Because of the importance of N and P, an adequate supply of both nutrients is needed from an early stage of growth.

The use of starter fertilizer to place nutrients close to the seed is common with corn growers. Starter fertilizer typically contains combinations of nutrients including N, P, potassium (K), and sulphur (S), and is usually side-banded near the seed (5 cm to the side and 5 cm below) or directly in-furrow (IF) to provide access to nutrients early in the growing season when root growth is limited (Bermudez and Mallarino 2004; Kaiser et al. 2016). Nutrient rates for IF placement are usually lower than for side-banded placement due to the risk of seedling toxicity and salt injury, but allow for less specialized equipment and faster planting speeds (Roth et al. 2006; Rehm and Lamb 2009; Kaiser et al. 2016). Regardless of SF placement, banding fertilizer close to the seed at planting instead of broadcasting, can increase nutrient use efficiency by increasing concentration near the roots and reducing overall nutrient loss (Jokela 1992; Kaiser et al. 2005; Grant and Flaten 2019).

In terms of corn growth response, starter fertilizers containing N plus P have increased early-season biomass (Kim et al. 2013; Roth et al. 2006; Rehm and Lamb 2009) and plant height (Mascagni and Boquet 1996; Bundy and Andraski 1999; Cromley et al. 2006; Kaiser et al. 2016), hastened time to reach the silking stage (Lauzon and Miller 1997; Cromley et al. 2006; Kaiser et al. 2016), and reduced grain moisture at harvest (Bullock et al. 1993; Kaiser et al. 2016). The increase in grain yield in response to SF is often less frequent and of lower magnitude than increases in early season growth (Bullock et al. 1993; Bermudez and Mallarino 2002; Vetsch and Randall 2002; Kaiser et al. 2005).

Corn yield response to SF can be impacted by management and environmental factors such as soil temperature, planting date, hybrid relative maturity (RM), soil test P concentration, SF nutrient composition, and previous crop. Cooler temperatures at planting generally favour greater phenotypic response to SF due to reduced root growth and reduced nutrient mobility (Kaspar and Bland 1992; Randall and Hoeft 1988). Delaying planting can limit exposure to cool soil temperatures, but may also limit growing degree days (GDD) available to the crop. Bundy and Andraski (1999) found that the probability of grain yield response to starter N plus P plus K was greatest when planting is delayed, especially with later RM hybrids, due to a hastening of development, leading to greater yield potential realization before a killing frost. Grain yield increases also tend to be more frequent on soils testing low in P, due to the large P requirement of corn for early growth (Randall and Hoeft 1988; Bermudez and Mallarino 2002; Wortmann et al. 2006). However, grain yield increases have also been observed on soils with medium or high STP concentration and have been attributed to increased positional availability of immobile nutrients, as well as nutrients other than P in the starter blend (Lauzon and Miller 1997; Mascagni and Boquet 1996; Bundy and Andraski 1999; Bermudez and Mallarino 2002). Since starter fertilizers usually contain two or more nutrients, it can be difficult to identify which specific nutrient is contributing to an increase in grain yield (Kaiser 2005; Mallarino et al. 2011).

The fertilizer requirement for crops can be also affected by rotational decisions that impact arbuscular mycorrhizal fungi (AMF) colonization (Plenchette and Morel 1996). Plant species such as corn that host AMF benefit from improved P uptake via hyphal networks in the soil (Bittman et al. 2004). As a result, corn is more likely to be deficient in P and have less early season growth and yield when following non-mycorrhizal crops such as canola (Bittman et al. 2004; Rogalsky 2017).

Although management and environmental factors can impact corn response to SF, an economic response may only be attained with certain corn hybrids. Teare and Wright (1990) evaluated 21 hybrids in Florida and observed positive grain yield increases in eight hybrids and a negative or no grain yield response in 13 hybrids with the application of starter N plus P. In Kansas, Gordon and Pierzynski (2006) reported that starter N plus P resulted in a reduction in thermal units required to reach silking, decreased grain moisture content at harvest, and increased grain yield for two out of four hybrids. However, hybrids did not differ in early season response, as starter N plus P increased growth and uptake of N and P at V6 of all hybrids. In contrast, other studies report that hybrids do not differ in grain yield response to starter N plus P (Mascagni and Bouquet 1996) or starter N plus P plus K (Buah et al. 1999).

Where hybrid differences have occurred, responsiveness to SF may be attributed to differences in root morphology between hybrids. Grain yield responsive hybrids are reported to have less root weight, root density, and rooting depth compared to non-responsive hybrids (Rhoads and Wright 1998; Gordon and Pierzynski 2006). Further, Rhoads and Wright (1998) suggested that differences in root characteristics between hybrids are more likely to influence response to starter N than P. In their study, P placed by the seed increased early root and shoot growth of all hybrids, whereas N placed close to the seed increased early root and shoot growth of the grain yield responsive hybrid, but not the non-responsive hybrid.

As the interest in corn production grows across Western Canada, acreage will continue to rise in non-traditional areas. In order to increase viability and profitability in these new environments, seed suppliers, corn growers, and agronomists require more knowledge of suitable hybrid selection and agronomic practices such as the use of starter fertilizer. In Manitoba, starter P has advanced maturity, reduced grain moisture, and increased grain yield of one corn hybrid, DKC26-28RIB (Rogalsky 2017). To expand our knowledge of SF responses for corn production in Manitoba, the objectives of this study were to evaluate the effects of starter N plus P and starter P alone on the growth, development, nutrient uptake and yield response of eight corn hybrids suited for Manitoba. Based on previous research elsewhere that demonstrated SF response can differ between hybrids, we hypothesized that response to starter N plus P as well as P alone would differ between hybrids for phenological development and grain yield.

2.3 Materials and Methods

2.3.1. Site Description

The starter N plus P experiment was conducted in 2017 and 2019 whereas the experiment to evaluate starter P alone was conducted in 2018 and 2019. Prior to each growing season, sixty soil cores (ten from each rep) from a depth of 0-15 cm were collected from each site. Composite samples from each rep were sent to AGVISE Laboratories (Northwood, ND, USA) for complete nutrient analysis (nitrogen, phosphorus, potassium, chloride, sulphur, boron, zinc, iron, manganese, copper, magnesium, calcium, sodium, organic matter, carbonates, soluble salts, pH, cation exchange capacity, and base saturation). Nitrate concentration was determined by cadmium reduction and phosphorus concentration by sodium bicarbonate extraction (Olsen). Soil phosphorus concentrations ranged from 10-38.5 mg kg^{-1} Olsen extractable P at 0-15 cm (Table 2.1).

Twelve site-years were used to measure the corn hybrid response to starter fertilizer experiments (Table 2.1). Site selection was determined based on locations of Bayer Crop Science's corn testing trials with fields changing each year depending on the cooperator's crop rotation. Unfortunately, adverse weather conditions resulted in minimal data collected from

Carberry 2017 (moisture stress; no harvest data), Winnipeg 2017 (late season stalk snap from wind; no harvest data), and Kane 2018 (moisture stress; no flowering and harvest data). In addition, data were not collected at Homewood 2018 due to early season green snap and at Roland 2019 due to poor emergence.

Table 2.1 Olsen extractable soil test phosphorus and previous crop for each site-year, prior to planting.

Site-Year	Olsen extractable phosphorus (mg kg^{-1})	Previous crop
Carberry 2017	38.5	Potato
Oakville 2017	-[a]	Soybean
Winnipeg 2017	13.5	Oats
Roland 2017	5[b]	Canola
Oakville 2018	10	Soybean
Homewood 2018	13	Soybean
Portage la Prairie 2018	22	Oats
Kane 2018	21	Soybean
Portage la Prairie 2019	25.5	Oats
Roland 2019	21	Oats
Winkler 2019	14	Canola
Oakville 2019	24.5	Soybean

[a] No soil sample taken at Oakville 2017
[b] Soil sample at Roland 2017 was a composite of the whole field, including area beyond the field plots (65 ha)

2.3.2. Experimental Design

Two field experiments were conducted between 2017 and 2019 to measure hybrid response to starter N plus P and starter P. Both studies were factorial experiments in a split plot design with six replicates. The fertilizer treatments for the starter N plus P experiment (2017 and 2019), were 22 kg P_2O_5 ha^{-1} and 6.7 kg N ha^{-1} applied in-furrow in the form of ammonium polyphosphate (APP, 10-34-0) and a control (no in-furrow N or P_2O_5). In the experiment to evaluate starter P (2018 and 2019), fertilizer treatments were 22 kg P_2O_5 ha^{-1} and 6.7 kg N ha^{-1}

applied in furrow as APP, and a control with 6.7 kg N ha^{-1} dribble banded pre-emergence in the form of urea-ammonium nitrate to match the rate of N applied in APP. Eight corn hybrids were chosen based on information provided from the seed company to represent the relative maturity range suitable for Manitoba (Table 2.2).

Table 2.2 Corn hybrids and required corn heat units (CHU) to reach maturity.

Hybrid	Corn Heat Units (CHU)^{a}
DKC23-17RIB	2075
DKC26-28RIB	2150
DKC26-40RIB	2150
DKC75-55RIB	2200
DKC30-07RIB	2350
DKC30-19RIB	2300
DKC32-12RIB	2450
DKC33-78RIB	2500

^{a} Corn heat unit ratings as provided by the seed company.

Corn plots were planted early to mid-May (Table 2.3), at 2.1 km hr^{-1}, to a depth of 4.5 cm and a population of 88 920 seeds ha^{-1} using a Kinze 3500® 8-row planter with the Almaco SeedPro 360® planting platform. The planter was equipped with row cleaners to remove residue and a liquid fertilizer system that applied in-furrow fertilizer via the seed firmers. Plots measured 3 m wide, 10 m long, and consisted of four rows with 76 cm spacing.

Prior to planting, urea, ammonium sulphate and potash were broadcast across each entire site and incorporated to 7 cm. The exceptions were Oakville 2017 and Roland 2017 where field fertilization occurred prior to soil nutrient sampling. Fertilizer application rates were above 200 kg ha^{-1} N and sufficient sulphur and potassium were applied to prevent nutrient deficiency for a 12.56 Mg ha^{-1} corn grain yield target (Table 2.4). No phosphorus was included in the broadcast fertilizer blend except at Oakville 2017 and Roland 2017 where the co-operator applied a fertilizer blend across each site prior to site establishment. All corn seeds were treated with both insecticides and fungicides (Appendix A.1.). Herbicide applications included a pre-emergence burn off and in-season applications (Appendix A.2.) as required to achieve adequate weed control. All herbicides were applied with a 12 m, tractor-mounted sprayer.

Table 2.3 Planting and harvest dates for corn experiments conducted between 2017 and 2019.

Site-Year	Planting date	Harvest date
Carberry 2017	May 17/17	N/A[a]
Oakville 2017	May 14/17	Oct 16/17
Winnipeg 2017	May 11/17	N/A[b]
Roland 2017	May 13/17	Oct 13/17
Oakville 2018	May 6/18	Oct 18/18
Homewood 2018	May 5/18	N/A[b]
Portage la Prairie 2018	May 7/18	Sept 30/18
Kane 2018	May 5/18	N/A[a]
Portage 2019	May 10/19	Oct 12/19
Roland 2019	May 8/19	N/A[c]
Winkler 2019	May 9/19	Nov 11/19
Oakville 2019	May 9/19	Nov 13/19[d]

[a] No harvest data due to moisture stress
[b] No harvest data due to green snap from wind
[c] No harvest data due to poor emergence
[d] Hand harvested due to snow and wind damage late in the season

Table 2.4 Rates of nitrogen, phosphate, potassium, and sulphur applied to the entire site before planting at each site-year.

Site-year	Nutrient applied[a]			
	N	P_2O_5	K_2O	S
	kg ha^{-1}			
Carberry 2017	200	0	40	20
Oakville 2017	200	34	0	15
Roland 2017	200	78	0	15
Winnipeg 2017	220	0	40	20
Homewood 2018	220	0	40	20
Kane 2018	220	0	40	20
Oakville 2018	220	0	40	20
Portage 2018	220	0	40	20
Oakville 2019	220	0	80	40
Portage 2019	230	0	57	28
Roland 2019	230	0	57	28
Winkler 2019	230	0	57	28

[a] Nutrients broadcasted and incorporated before planting as a blend of urea, monoammonium phosphate, potash, and/or ammonium sulphate, depending on site requirements for N, P, K, and S, respectively

2.3.3. Weather Conditions

Growing season temperature and precipitation data for each site-year were attained from Climate Fieldview (The Climate Corporation 2020). Daily temperature readings were used to calculate daily and total corn heat unit (CHU) accumulation.

2.3.4. Early season crop observations

Corn density was determined by counting all plants in the centre two rows of each plot after the V2 growth stage. Early plant biomass was collected at the V4 to V5 growth stage by randomly selecting 10 plants from the outside two rows of a plot and cutting the plants at the soil surface. Plant samples were placed in a drying room at 40°C until a consistent moisture concentration was achieved. Samples where then weighed and shipped to AGVISE Laboratories (Northwood, ND, USA) to be ground and analyzed for tissue phosphorus concentration. Phosphorus uptake at the V4-V5 stage was then calculated from the dried plant weight and plant P concentration.

Seedling vigour was measured at V4 to V6 on the centre two rows of each plot in 2018 and 2019 to capture the rate of vegetative growth and development. Seedling vigour was measured as a visual rating on a scale of one (greatest amount of vegetative growth) to nine (smallest amount of vegetative growth).

2.3.5. Mid-season crop observations

Days required to reach silking (R1) was recorded when 50% of the plants in the centre two rows of each plot had silks showing.

Plant height was recorded from five randomly selected plants from the centre two rows from each plot. Plant height was captured after the plant had reached maximum height (at R2, after tasseling) and was recorded as the distance between the soil surface and the flag leaf node. Height measurements reported for each plot are averages of the five measurements.

2.3.6. Harvest Measurements

Grain yield, moisture, and test weight were measured by harvesting the centre two rows of each plot using a plot combine (New Holland TR88® equipped with an Almaco Seed Spector LRX® weigh system). Grain moisture content was corrected to 155 g kg^{-1} moisture. At the Winkler 2019 location, a combination of wind and snow resulted in lodged plants and dropped ears; therefore, grain yield and grain moisture at this site-year were collected by hand harvesting 32 ears from standing plants (one ear per plant) in the centre two rows and manually feeding them into a plot combine.

2.3.7. Statistical Analysis

Data were statistically analyzed using the Proc Mixed procedure and tested for normality of residuals using the Proc Univariate procedure and Shapiro-Wilk statistic in SAS 9.4. None of the data required transformation as the Shapiro-Wilk statistic was above 0.9 for all observations. Results were considered significant when $P \leq 0.05$. The Tukey-Kramer test was used to assign letter groupings to treatment means for significant main effects or interactions that were related to starter fertilizer. In the statistical model, site-year, treatment, and hybrid were treated as fixed effects. Site-year was designated a fixed effect to allow for the comparison of how site-year specific factors influenced the response of hybrids to starter fertilizer. Block(site-year) and treatment*block(site-year) were treated as random effects.

The main focus of the experiments was to evaluate the effects of starter fertilizer on corn hybrid. Therefore, letter groupings for treatment means for significant main effects or interactions related to starter fertilizer are presented in the tables in this chapter. Letter groupings for treatment means for the interactions between hybrid and site-years are presented in the appendices.

2.4 Results

2.4.1. Starter N plus P

At all site-years, CHU accumulation (Table 2.5) was sufficient for each hybrid to reach physiological maturity (2150-2400 CHU) before a killing frost. However, growing season precipitation was below the 30-year average at the 2017 site-years (Climate FieldView 2020). At the 2019 site-years, growing season precipitation was in line with the 30-year average, but a large proportion of the precipitation occurred in September, when crop water requirement is low (Kranz 2008). In 2019, precipitation between May and August was normal for Winkler 2019 but 68% and 63% of the 30-year historical average at Oakville 2019 and Portage 2019 respectively (Table 2.5). Stand counts were not affected by the application of starter N plus P (Table 2.6). However, there was a site*hybrid interaction where population of some hybrids at V4 differed between site-years.

Table 2.5 Total corn heat unit (CHU) accumulation, monthly, total, and historical precipitation at all site-years.

Site Year	CHU_{total}[a]	Growing season Precipitation						30 Year Historical Precipitation					
		May	June	July	Aug.	Sept.	Total	May	June	July	Aug.	Sept.	Total
		mm											
Carberry 2017	-[b]	9	74	24	32	81	220	47	84	76	63	40	310
Oakville 2017	2770	15	70	47	13	85	230	39	88	73	66	45	311
Roland 2017	2675	28	65	72	31	82	278	55	97	76	65	51	344
Winnipeg 2017	-[b]	21	56	74	15	86	228	44	89	76	75	47	331
Kane 2018	-[b]	37	83	76	29	62	273	68	104	74	67	54	367
Oakville 2018	2880	27	108	41	21	122	319	57	90	71	61	48	327
Portage 2018	2867	39	101	41	22	108	312	59	90	69	54	49	330
Oakville 2019	2780	26	46	52	68	182	374	50	97	69	65	49	330
Portage 2019	2723	27	37	62	40	165	331	46	87	73	54	46	306
Winkler 2019	2704	39	80	103	77	200	499	61	108	77	66	54	366

[a] Corn heat unit accumulation reported from date of planting to date of first frost or harvest.
[b] Location terminated before harvest. CHU not reported.

Starter nitrogen plus phosphorus significantly increased early season biomass at V4-V5 compared to the control (Table 2.7). When averaged across all hybrids and site-years, early season biomass was 17 kg ha^{-1} (9.1%) greater with starter N plus P compared to the no starter control. Analysis of variance did not indicate an interaction between hybrid*fertilizer or site-year*fertilizer for early season biomass response.

Seedling vigour was evaluated only at Oakville 2019, Portage 2019, and Winkler 2019 in the experiment to evaluate starter N plus P. Seedling vigour was not influenced by a starter N plus P or the interaction between hybrid*fertilizer or site-year*fertilizer (Table 2.8).

Corn tissue P concentration was increased with starter N plus P. Phosphorus concentrations at V4-V5 were 0.6 g kg^{-1} greater in plots receiving starter N plus P compared to the no starter control (Table 2.9). Although hybrids differed in tissue P concentration, the increase in P concentration as a result of starter N plus P did not differ between hybrids and there was no fertilizer*hybrid interaction. However, a site-year*fertilizer interaction resulted in the increase in corn tissue P concentrations being greatest at Carberry 2017 (1.5 g kg^{-1}), Oakville 2017 (1.2 g kg^{-1}), and Roland 2017 (1.1 g kg^{-1}).

Tissue P concentration and early season biomass were used to calculate P uptake; thus, results generally follow the same trends as reported earlier for those measurements. Phosphorus uptake was 0.2 kg ha^{-1} (22%) greater with starter N plus P compared to the control when averaged across hybrids and site-years (Table 2.10). The increase in P uptake generally occurred across all hybrids, but a site-year*starter interaction resulted in significant increases in P uptake only at Carberry 2017, Oakville 2017, and Roland 2017, which had increases of 36%, 21% and 50%, respectively, over the control.

The days required for corn to reach silking (Table 2.11) were less for the starter N plus P treatment, compared to the control receiving no starter, when averaged across site-years and hybrids. The overall reduction of 0.5 days did not differ with hybrid. However, there was a site-year*fertilizer interaction where the reduction in days to silking for the starter treatment compared to the control was significant only at Carberry 2017, Roland 2017, and Winkler 2019, each of which had reductions of one day.

Table 2.6 Plant count at V4 as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		plants ha^{-1}									
Carberry 2017	No Starter	85118	86001	85228	85780	85007	85559	86222	85670	85573	85718a
	Starter N+P	86553	86553	85118	87105	84786	85118	86222	85449	85863	
Oakville 2017	No Starter	84345	84124	82578	83682	82799	82247	84566	83903	83531	83413b
	Starter N+P	82910	83793	82468	84786	82137	82468	83351	84455	83296	
Roland 2017	No Starter	82137	84676	83793	84124	85890	85228	84676	82358	84110	84103b
	Starter N+P	81254	83241	83241	83130	85780	85007	85338	85780	84096	
Winnipeg 2017	No Starter	83682	82468	83020	83682	84455	83351	83682	83020	83420	83413b
	Starter N+P	84786	82468	82689	83572	84455	83793	81916	83572	83406	
Oakville 2019	No Starter	83602	84014	82939	84794	83793	81695	84345	83462	83581	83998b
	Starter N+P	84263	85118	84234	84234	84445	83844	84280	84904	84415	
Portage 2019	No Starter	81916	82247	81254	82358	82247	82468	82799	83020	82289	82264c
	Starter N+P	81916	82578	81474	82689	82910	81856	81695	82799	82240	
Winkler 2019	No Starter	82468	81474	82578	82910	83130	82026	81806	79818	82026	81923c
	Starter N+P	81033	81254	83130	81474	81033	82247	83351	81033	81819	
All site-years	No Starter	83324	83572	83056	83904	83903	83225	84014	83036	83504	
	Starter N+P	83245	83572	83193	83856	72792	83476	83736	83999	82234	
Hybrid		83284	83572	83125	83880	83776	83351	83875	83517		

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	0.5443
Site-year*Fert	6	0.4963
Hybrid	7	0.1151
Site-year*Hybrid	42	0.0012
Fert*Hybrid	7	0.5686
Site-year*Fert*Hybrid	42	0.8563
Coeff Var (C.V.)		2.8%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$).

Table 2.7 Early-season biomass at V4-V6, as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		kg ha^{-1}									
Carberry 2017	No Starter	169	180	181	187	191	168	180	163	177	191b
	Starter N+P	224	215	190	205	206	175	215	209	205	
Oakville 2017	No Starter	274	257	257	246	253	244	246	254	254	256a
	Starter N+P	270	252	256	260	249	253	254	265	257	
Roland 2017	No Starter	196	199	198	198	199	196	197	208	199	206b
	Starter N+P	221	218	213	210	206	203	213	214	212	
Winnipeg 2017	No Starter	255	234	257	253	243	247	244	239	247	255a
	Starter N+P	282	275	258	262	267	254	251	257	263	
Oakville 2019	No Starter	216	191	208	230	186	201	213	218	217	224ab
	Starter N+P	249	300	230	208	233	204	273	234	241	
Portage 2019	No Starter	151	112	142	113	106	110	117	95	118	121c
	Starter N+P	159	115	160	121	112	115	123	91	125	
Winkler 2019	No Starter	112	105	118	93	96	101	98	87	101	111c
	Starter N+P	139	113	129	127	112	121	124	102	121	
All site-years	No Starter	196	182	194	189	182	181	185	181	186b	
	Starter N+P	221	213	205	199	198	189	208	196	203a	
Hybrid[a]		208A	198ABC	200AB	194BC	198BC	185C	196ABC	188BC		

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	0.0003
Site-year*Fert	6	0.5016
Hybrid	7	<.0001
Site-year*Hybrid	42	0.0063
Fert*Hybrid	7	0.0834
Site-year*Fert*Hybrid	42	0.1108
Coeff Var (C.V.)		33.7%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.8 Seedling vigour scores at V4-V6, as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		Seedling vigour[a]									
Oakville 2019	No Starter	3.4	4.3	2.4	5.0	4.0	4.5	4.0	5.7	4.2	4.4
	Starter N+P	4.0	4.2	3.7	4.2	5.9	5.5	3.9	6.5	4.7	
Portage 2019	No Starter	2.5	4.0	2.2	3.5	4.5	4.0	3.8	5.0	3.7	3.7
	Starter N+P	2.7	4.2	2.4	3.5	4.3	4.0	3.2	5.3	3.7	
Winkler 2019	No Starter	4.3	4.7	3.5	5.3	5.0	4.7	4.8	6.7	4.9	4.4
	Starter N+P	3.5	4.0	3.5	3.2	4.7	3.3	3.5	5.2	3.9	
All site-years	No Starter	3.4	4.3	2.7	4.6	4.5	4.4	4.2	5.8	4.2	
	Starter N+P	3.4	4.1	3.2	3.6	5.0	4.3	3.5	5.7	4.1	
Hybrid[b]		3.4DE	4.2BCD	2.9E	4.1BCD	4.7B	4.3BC	3.9CD	5.7A		

ANOVA	DF	*Pr>F*
Site-year	2	0.2687
Fert	1	0.5004
Site-year*Fert	2	0.0582
Hybrid	7	<.0001
Site-year*Hybrid	15	0.6712
Fert*Hybrid	7	0.1422
Site-year*Fert*Hybrid	15	0.7080
Coeff Var (C.V.)		39.5%

[a] Seedling vigour was scored on a scale of 1-9. 1 = most vigorous; 9 = least vigorous.
[b] Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.9 Early-season phosphorus concentration at V4-V6, as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean [a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		g kg^{-1}									
Carberry 2017	No Starter	6.0	5.0	5.8	6.3	6.7	6.2	5.1	5.3	5.8bc	6.6a
	Starter N+P	7.6	8.0	6.8	7.6	6.8	7.7	7.1	7.0	7.3a	
Oakville 2017	No Starter	5.4	5.4	5.4	5.7	5.4	5.8	5.7	5.5	5.5cd	6.1ab
	Starter N+P	6.1	6.7	6.4	6.8	7.3	7.2	6.9	6.3	6.7ab	
Roland 2017	No Starter	3.3	3.1	3.2	3.2	2.9	3.1	3.1	3.0	3.1f	3.6d
	Starter N+P	4.0	4.6	4.0	4.4	4.4	4.3	4.1	3.8	4.2e	
Winnipeg 2017	No Starter	5.0	4.9	5.0	4.9	4.9	5.1	4.1	4.9	5.0c	5.1bc
	Starter N+P	5.1	5.2	5.2	5.3	5.2	5.3	5.4	5.2	5.2c	
Oakville 2019	No Starter	4.4	4.3	4.3	4.4	4.6	4.8	4.6	4.3	4.5de	4.5cd
	Starter N+P	4.4	4.4	4.4	4.6	4.7	4.8	5.0	4.6	4.6cde	
Portage 2019	No Starter	4.2	4.6	4.6	4.8	4.5	5.0	4.9	4.3	4.6cde	4.6cd
	Starter N+P	4.4	4.6	4.3	5.1	4.5	5.3	4.6	4.3	4.6cde	
Winkler 2019	No Starter	4.3	4.2	4.2	4.2	4.2	4.3	4.4	4.2	4.3def	4.2cd
	Starter N+P	4.0	3.8	4.0	4.0	4.3	4.8	4.4	4.1	4.2ef	
All site-years	No Starter	4.7	4.5	4.6	4.8	4.8	4.9	4.7	4.5	4.7	
	Starter N+P	5.1	5.3	5.0	5.4	5.3	5.6	5.4	5.1	5.3	
Hybrid[a]		4.9B	4.9B	4.8B	5.1AB	5.0AB	5.3A	5.0AB	4.8B		

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	<.0001
Site-year*Fert	6	<.0001
Hybrid	7	<.0001
Site-year*Hybrid	42	0.6804
Fert*Hybrid	7	0.3431
Site-year*Fert*Hybrid	42	0.35
Coeff Var (C.V.)		27.5%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.10 Early-season phosphorus uptake at V4-V6, as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean [a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		kg ha^{-1}									
Carberry 2017	No Starter	1.1	0.9	1.1	1.2	1.4	1.1	0.9	0.9	1.1cd	1.3ab
	Starter N+P	1.7	1.7	1.3	1.6	1.4	1.4	1.5	1.5	1.5ab	
Oakville 2017	No Starter	1.5	1.4	1.4	1.4	1.4	1.4	1.5	1.4	1.4bc	1.6a
	Starter N+P	1.7	1.7	1.6	1.8	1.8	1.8	1.7	1.7	1.7a	
Roland 2017	No Starter	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6eg	0.8cd
	Starter N+P	0.9	1.0	0.9	0.9	0.9	0.9	0.9	0.8	0.9df	
Winnipeg 2017	No Starter	1.3	1.2	1.3	1.3	1.2	1.3	1.3	1.2	1.2bcd	1.3ab
	Starter N+P	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.4abc	
Oakville 2019	No Starter	0.9	0.8	0.9	1.0	0.9	1.0	1.0	0.9	0.9de	1.0bc
	Starter N+P	1.1	1.3	1.0	1.0	1.1	1.0	1.4	1.1	1.1bcd	
Portage 2019	No Starter	0.6	0.5	0.7	0.5	0.5	0.6	0.6	0.4	0.5efg	0.6d
	Starter N+P	0.7	0.5	0.7	0.6	0.5	0.6	0.6	0.4	0.6efg	
Winkler 2019	No Starter	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4g	0.5d
	Starter N+P	0.6	0.4	0.5	0.6	0.5	0.6	0.5	0.4	0.5fg	
All site-years	No Starter	0.9	0.8	0.9	0.9	0.9	0.9	0.9	0.8	0.9	
	Starter N+P	1.1	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.1	
Hybrid[a]		1.0A	1.0AB	1.0AB	1.0AB	1.0AB	1.0AB	1.0AB	0.9B		

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	<.0001
Site-year*Fert	6	0.0029
Hybrid	7	0.0315
Site-year*Hybrid	42	0.579
Fert*Hybrid	7	0.0762
Site-year*Fert*Hybrid	42	0.1158
Coeff Var (C.V.)		48.5%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.11 Days from planting to silking as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean [a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		Days after planting									
Carberry 2017	No Starter	71.3	72.3	72.7	71.0	74.5	73.2	73.8	74.2	72.9f	72.3e
	Starter N+P	69.2	71.8	70.7	69.0	73.2	71.8	73.8	74.8	71.8g	
Oakville 2017	No Starter	74.5	75.8	75.5	75.0	78.0	76.8	78.2	78.3	76.5e	76.3d
	Starter N+P	73.5	75.3	74.5	74.2	78.2	76.5	77.7	78.3	76e	
Roland 2017	No Starter	78.2	79.8	79.2	79.0	83.2	80.5	83.0	83.8	80.8b	80.2b
	Starter N+P	77.2	78.0	78.0	77.2	81.3	79.8	82.3	82.5	79.5cd	
Winnipeg 2017	No Starter	79.7	82.5	80.7	82.3	84.7	83.3	85.2	84.8	82.9a	82.7a
	Starter N+P	79.5	81.5	80.3	80.8	85.7	82.7	84.8	85.2	82.6a	
Oakville 2019	No Starter	77.6	77.5	77.8	77.2	81.7	78.5	81.3	82.2	79.2cd	79.3bc
	Starter N+P	77.6	76.5	78.2	77.2	82.1	78.8	81.3	82.4	79.3cd	
Portage 2019	No Starter	74.3	75.7	74.2	75.0	78.5	76.3	78.0	78.7	76.3e	76.1d
	Starter N+P	74.0	74.5	74.2	75.0	77.8	76.0	77.0	78.3	75.9e	
Winkler 2019	No Starter	78.0	78.5	79.0	77.5	82.0	79.2	81.0	81.3	79.6bc	79.1c
	Starter N+P	77.5	77.3	77.8	77.0	79.5	77.7	79.7	81.8	78.5d	
All site-years	No Starter	76.2	77.5	77.0	76.7	80.4	78.3	80.1	80.5	78.3	
	Starter N+P	75.5	76.4	76.2	75.8	79.7	77.6	79.5	80.5	77.7	
Hybrid[a]		75.9F	76.9D	76.6DE	76.3EF	80.0AB	77.9C	79.8B	80.5A		

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	<.0001
Site-year*Fert	6	0.0157
Hybrid	7	<.0001
Site-year*Hybrid	42	<.0001
Fert*Hybrid	7	0.0590
Site-year*Fert*Hybrid	42	0.2274
Coeff Var (C.V.)		4.9%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Across all site-years and hybrids, plant height at the R2 growth stage was 2 cm shorter with starter N plus P compared to the control (Table 2.12). The decrease in height was not influenced by hybrid, but the site-year*fertilizer interaction was significant. The height difference was significant only at Carberry 2017, where plots receiving starter N plus P were 7 cm shorter than the control.

At harvest, grain moisture content was not influenced by a fertilizer or fertilizer*hybrid interaction (Table 2.13). Analysis of variance indicated a significant site-year*fertilizer interaction, but the interaction was not substantial enough to result in a significant effect of fertilizer on grain moisture at any particular site according to the Tukey-Kramer test.

For grain yield, starter N plus P application resulted in an overall increase of 256 kg ha^{-1} (2.7%) relative to the control (Table 2.14). However, a hybrid*fertilizer interaction resulted in the increase being significant for only one out of eight individual hybrids, DKC26-28RIB. Compared to the control, grain yield of DKC26-28RIB was 789 kg ha^{-1} (8.4%) greater with starter N plus P. An interaction for site-year*fertilizer resulted in starter N plus P increasing grain yield at Winkler 2019 by 583 kg ha^{-1} (6.1%) compared to the control, but no increases in grain yield over the control at the other four individual site-years.

Table 2.12 Plant height at R2 growth stage as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean [a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		cm									
Carberry 2017	No Starter	200	212	197	200	210	204	212	215	206g	203d
	Starter N+P	187	203	200	193	203	194	209	206	199h	
Oakville 2017	No Starter	230	237	229	235	245	230	245	249	238a	237a
	Starter N+P	229	240	226	233	243	229	240	245	236ab	
Roland 2017	No Starter	200	216	210	206	218	202	214	211	210efg	209d
	Starter N+P	204	209	204	203	213	203	214	209	207fgh	
Oakville 2019	No Starter	217	220	217	217	226	211	228	221	220bcd	227ab
	Starter N+P	208	220	213	218	227	211	225	218	217abc	
Portage 2019	No Starter	224	223	218	228	225	224	230	231	225cde	219c
	Starter N+P	218	236	225	232	230	232	226	233	229def	
Winkler 2019	No Starter	208	219	206	211	210	204	217	199	209fgh	210d
	Starter N+P	201	208	211	210	202	208	210	205	207gh	
All site-years	No Starter	213	221	213	216	222	213	225	221	218	
	Starter N+P	208	219	213	215	220	213	221	219	216	
Hybrid[a]		211C	220A	213BC	215B	221A	213BC	222A	220A		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.0061
Site-year*Fert	5	0.0131
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.4194
Site-year*Fert*Hybrid	35	0.3277
Coeff Var (C.V.)		7.3%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.13 Corn grain moisture at harvest as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean [a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		g kg^{-1}									
Oakville 2017	No Starter	235	258	257	266	250	276	264	263	258a	257a
	Starter N+P	236	250	253	258	250	273	257	260	255a	
Roland 2017	No Starter	218	236	225	225	217	227	223	234	226bc	221c
	Starter N+P	209	216	221	219	205	221	217	227	217c	
Oakville 2019	No Starter	224	237	224	228	245	233	242	245	235b	236b
	Starter N+P	229	238	227	225	250	239	242	252	238b	
Portage 2019	No Starter	236	259	245	269	273	264	284	303	267a	268a
	Starter N+P	241	271	253	270	278	272	276	303	270a	
Winkler 2019	No Starter	222	218	213	213	232	234	238	243	227bc	227bc
	Starter N+P	224	216	228	216	231	229	234	236	227bc	
All site-years	No Starter	227	242	233	240	243	247	250	257	242	
	Starter N+P	228	238	236	237	243	247	245	256	241	
Hybrid[a]		227E	240CD	235D	239CD	243BC	247B	248B	256A		

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.3736
Site-year*Fert	4	0.0249
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.3761
Site-year*Fert*Hybrid	28	0.8572
Coeff Var (C.V.)		10.0%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.14 Corn grain yield at harvest as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[b]	Site Mean[b]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		kg ha^{-1a}									
Oakville 2017	No Starter	10245	11130	10737	10700	10033	10756	11541	11501	10830a	10858a
	Starter N+P	10287	11173	10647	10726	10568	10737	11563	11384	10886a	
Roland 2017	No Starter	7599	8064	8533	8045	7433	8177	8718	8030	8075c	8303c
	Starter N+P	8304	8762	8693	8375	7755	8756	8709	8881	8529bc	
Oakville 2019	No Starter	10412	10213	11372	9580	10572	10566	11771	11081	10696a	10654a
	Starter N+P	10268	10871	11589	9995	10470	9685	11019	10993	10611a	
Portage 2019	No Starter	7876	7925	9225	8457	7907	8731	9484	9549	8644bc	8779c
	Starter N+P	7857	9215	9246	8464	8162	8716	9752	9899	8914bc	
Winkler 2019	No Starter	8638	9456	8495	8576	9497	10232	10856	10184	9492b	9783b
	Starter N+P	8691	10716	8562	9743	10096	10617	11117	11056	10075a	
All site-years[b]	No Starter	8954F	9358DEF	9672BCDE	9072EF	9088EF	9692BCDE	10474A	10069ABC	9547	
	Starter N+P	9081EF	10147AB	9747BCD	9461CDEF	9410DEF	9702BCDE	10432A	10443A	9803	
Hybrid[b]		9017C	9752B	9711B	9266C	9249C	9697B	10453A	10256A		

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0005
Site-year*Fert	4	0.0204
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.0336
Site-year*Fert*Hybrid	28	0.9064
Coeff Var (C.V.)		14.8%

[a] Grain yield corrected to 155 g kg^{-1}.
[b] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

2.4.2. Starter P

Similar to the starter N plus P experiment, corn heat unit accumulation at each site-year was sufficient for hybrids to reach physiological maturity before a killing frost (Table 2.4). Growing season precipitation was below the 30-year average at the 2018 site-years (Climate FieldView 2020) but not at the 2019 site-years. However, precipitation between May and August, during the main portion of the growing season, was 68% and 63% of the 30-year historical average at Oakville 2019 and Portage 2019, respectively. Stand counts did not differ between the control and plots receiving starter P (Table 2.15). Application of starter P alone did not influence early season biomass of any hybrid or at any site-year (Table 2.16). Analysis of variance indicated a significant site-year*fertilizer interaction for both seedling vigour rating (Table 2.17) and tissue P concentration (Table 2.18), but the interaction was not substantial enough to result in a significant effect of fertilizer at any individual site-year according to the Tukey-Kramer test. Starter P application did not influence P uptake (Table 2.19), reflecting the absence of increases in early season biomass and tissue P concentration. Although no early season responses to starter P were observed, days to silking (Table 2.20) were reduced slightly. Starter P resulted in a 0.2-day reduction in days to reach the silking stage which did not differ by hybrid. However, the site-year*treatment interaction indicated the reduction in days to silking was significant at Winkler 2019 (1.1 day), but not the other five site-years. Plant height at R2 was not affected by starter P or the interaction of starter P treatment with hybrid or site-year (Table 2.21).

At harvest, grain moisture content when averaged across all site-years and hybrids was slightly greater (4 g kg^{-1}) with starter P compared to without (Table 2.22). However, a significant site-year*fertilizer*hybrid interaction indicated that the effect of fertilizer*hybrid was not consistent across site-years. The only site-year where a fertilizer*hybrid interaction was significant was at Portage 2018, where starter P reduced grain moisture content of DKC26-28RIB by 52 g kg^{-1} and increased grain moisture content of DKC33-78RIB by 45 g kg^{-1} compared to the control treatment (Appendix C.13). Starter P did not affect grain moisture content of the other six hybrids at Portage 2018 or grain moisture content of any hybrid at the other four site-years.

When averaged across all site-years and hybrids, starter P resulted in a 161 kg ha^{-1} (1.8%) increase in grain yield, relative to the control that received no starter P (Table 2.23). However, there was a fertilizer*hybrid interaction and when each hybrid's yield response was analyzed individually, the yield increase was significant only for DKC26-28RIB. Compared to the control, grain yield of DKC26-28RIB was 1022 kg ha^{-1} (12%) greater with starter P. There was also a site-year*fertilizer interaction, resulting in starter P increasing grain yield across all hybrids at Winkler 2019 by 542 kg ha^{-1} (5.7%) compared to the control, but no increase in grain yield over the control at the other four site-years.

Table 2.15 Plant count at V4 as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		Plants ha^{-1}									
Kane 2018	Starter N	84676	84345	85338	84786	84897	83572	83351	84786	84469	84338a
	Starter N+P	84455	84786	84014	83241	84786	84234	84345	83793	84207	
Oakville 2018	Starter N	83682	85559	84345	84897	83903	85228	84345	83793	84469	84848a
	Starter N+P	84345	85338	85007	85338	84897	86553	85780	84566	85228	
Portage 2018	Starter N	85780	84014	84676	84897	85559	82910	83793	84897	84566	84248a
	Starter N+P	84455	83462	82358	84897	83462	84124	85228	83462	83931	
Oakville 2019	Starter N	82468	82578	83572	82799	81254	82247	82578	81474	82371	84454a
	Starter N+P	81916	82578	81474	82689	82910	81872	81695	82799	82242	
Portage 2019	Starter N	84897	84345	84566	84566	85117	83903	84014	84124	84442	82312b
	Starter N+P	84266	85118	84234	84234	84562	83935	85396	84994	84592	
Winkler 2019	Starter N	82910	82247	81254	84234	82358	82689	81364	80591	82206	81944b
	Starter N+P	81033	81254	83130	81474	81033	82247	83351	81033	81819	
All site-years	Starter N	84069	83848	83958	84363	83848	83425	83241	83278	83754	
	Starter N+P	83412	83756	83370	83646	83608	83828	84299	83441	83670	
Hybrid		83740	83802	83664	83912	83728	83634	83687	83359		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.6525
Site-year*Fert	5	0.3355
Hybrid	7	0.7545
Site-year*Hybrid	35	0.5241
Fert*Hybrid	7	0.1036
Site-year*Fert*Hybrid	35	0.3382
Coeff Var (C.V.)		2.6%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different (*P*≤0.05).

Table 2.16 Early-season biomass at V4-V6, as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		kg ha^{-1}									
Kane 2018	Starter N	439.2	464.8	402.4	423.9	400.1	370.2	415.4	407.9	415.5	444a
	Starter N+P	458.8	475.1	448.9	438.2	443.2	420.3	457.6	420.9	445.4	
Oakville 2018	Starter N	183.6	175.3	158.3	172.4	159.3	142.6	189.0	164.9	168.2	159c
	Starter N+P	152.2	162.9	175.8	176.8	169.1	128.8	157.4	142.0	158.1	
Portage 2018	Starter N	228.7	216.1	228.7	221.4	214.2	222.3	257.1	233.7	227.8	226b
	Starter N+P	230.9	215.3	260.8	237.9	230.0	217.6	212.7	209.4	226.8	
Oakville 2019	Starter N	262.5	166.6	217.3	233.6	230.0	238.6	226.0	226.7	225.2	223b
	Starter N+P	248.3	300.1	229.9	207.6	232.5	204.7	272.8	234.2	241.3	
Portage 2019	Starter N	138.9	119.9	138.9	119.9	112.8	108.8	130.9	91.7	120.2	103c
	Starter N+P	159.0	115.2	159.8	121.1	111.9	115.3	123.2	90.6	124.5	
Winkler 2019	Starter N	110.3	101.7	114.0	93.4	94.6	94.4	108.3	81.5	99.8	110c
	Starter N+P	139.5	113.4	128.6	126.7	112.0	120.6	124.5	101.8	120.9	
All site-years	Starter N	227.2	207.4	209.9	210.7	201.8	196.1	221.1	201.1	209.4	
	Starter N+P	231.4	230.3	234.0	218.1	216.5	201.2	224.7	199.8	219.5	
Hybrid[a]		221A	220A	226A	220A	212A	211A	226A	204A		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.1015
Site-year*Fert	5	0.4072
Hybrid	7	<.0001
Site-year*Hybrid	35	0.4786
Fert*Hybrid	7	0.4585
Site-year*Fert*Hybrid	35	0.0926
Coeff Var (C.V.)		56.2%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.17 Seedling vigour at V4-V6, as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[b]	Site Mean[b]
		Seedling vigour[a]									
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
Kane 2018	Starter N	3.2	2.7	4.3	3.7	4.0	5.0	2.8	4.8	3.8abc	3.7ab
	Starter N+P	3.2	2.7	4.0	3.5	3.0	5.0	2.8	4.5	3.6abc	
Oakville 2018	Starter N	2.2	3.3	3.3	3.3	3.5	4.5	2.8	4.0	3.4abc	3.6ab
	Starter N+P	3.5	3.2	3.5	3.2	2.8	5.8	4.0	4.5	3.8abc	
Portage 2018	Starter N	3.2	2.7	3.3	2.8	3.8	3.2	2.3	3.8	3.1bc	2.9b
	Starter N+P	2.5	2.8	2.5	2.2	2.8	2.7	2.0	3.0	2.6c	
Oakville 2019	Starter N	2.5	4.2	2.2	3.2	4.0	4.3	3.3	6.5	3.8abc	4.3a
	Starter N+P	4.0	4.2	3.7	4.2	5.9	5.5	3.9	6.5	4.7ab	
Portage 2019	Starter N	2.8	3.8	2.3	3.7	3.5	4.2	2.2	5.0	3.4abc	3.6ab
	Starter N+P	2.7	2.2	4.2	3.5	4.3	4.0	3.2	5.3	3.7abc	
Winkler 2019	Starter N	4.2	4.8	4.0	4.8	4.8	5.5	3.8	6.8	4.8a	4.4a
	Starter N+P	3.5	4.0	3.5	3.2	4.8	3.3	3.5	5.2	3.9abc	
All site-years	Starter N	3.0	3.6	3.2	3.6	3.9	4.5	2.9	5.2	3.7	
	Starter N+P	3.2	3.2	3.6	3.3	3.9	4.4	3.2	4.8	3.7	
Hybrid[b]		3.1D	3.4CD	3.4D	3.4CD	3.9BC	4.4B	3.0D	5.0A		

ANOVA	DF	*Pr>F*
Site-year	5	0.003
Fert	1	0.8469
Site-year*Fert	5	0.0179
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.6034
Site-year*Fert*Hybrid	35	0.6736
Coeff Var (C.V.)		41.9%

[a] Seedling vigour was scored on a scale of 1-9. 1 = most vigorous; 9 = least vigorous.
[b] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.18 Early-season phosphorus concentration at V4-V6, as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		g kg^{-1}									
Kane 2018	Starter N	3.32	3.40	3.22	3.55	3.68	3.52	3.92	3.52	3.52cd	3.32c
	Starter N+P	2.93	3.10	3.02	3.08	3.38	3.08	3.45	3.00	3.13d	
Oakville 2018	Starter N	3.32	3.48	3.53	3.65	3.57	3.86	3.62	3.70	3.59cd	3.63c
	Starter N+P	3.53	3.47	3.48	3.55	3.85	4.02	3.81	3.65	3.67bc	
Portage 2018	Starter N	3.58	3.63	3.43	3.85	3.53	3.83	3.70	3.42	3.62cd	3.53c
	Starter N+P	3.12	3.45	3.30	3.37	3.42	3.65	3.65	3.48	3.43cd	
Oakville 2019	Starter N	4.43	4.38	4.46	4.66	4.63	4.83	5.00	4.53	4.62a	4.62a
	Starter N+P	4.35	4.43	4.40	4.58	4.72	4.85	5.05	4.61	4.62a	
Portage 2019	Starter N	4.62	4.68	4.25	4.57	4.40	4.77	4.32	4.48	4.51a	4.48ab
	Starter N+P	4.37	4.68	4.32	5.01	4.48	5.30	4.63	4.33	4.64a	
Winkler 2019	Starter N	4.02	4.33	3.90	4.37	4.23	4.72	4.28	4.27	4.26a	4.22b
	Starter N+P	3.95	3.83	4.00	3.98	4.27	4.82	4.39	4.12	4.17ab	
All site-years	Starter N	3.88	3.99	3.80	4.11	4.01	4.25	4.14	3.99	4.02	
	Starter N+P	3.71	3.83	3.75	3.93	4.02	4.29	4.16	3.86	3.94	
Hybrid[a]		3.79D	3.90CD	3.78D	4.02BC	4.01BC	4.27A	4.15AB	3.93CD		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.1221
Site-year*Fert	5	0.0393
Hybrid	7	<.0001
Site-year*Hybrid	35	0.0685
Fert*Hybrid	7	0.4619
Site-year*Fert*Hybrid	35	0.9308
Coeff Var (C.V.)		17.3%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.19 Early-season phosphorus uptake at V4-V6, as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		kg ha^{-1}									
Kane 2018	Starter N	1.449	1.586	1.301	1.522	1.464	1.306	1.637	1.388	1.457	1.428a
	Starter N+P	1.338	1.477	1.370	1.355	1.503	1.298	1.595	1.257	1.399	
Oakville 2018	Starter N	0.603	0.607	0.559	0.625	0.571	0.558	0.674	0.597	0.599	0.586cd
	Starter N+P	0.542	0.543	0.611	0.630	0.640	0.519	0.584	0.507	0.572	
Portage 2018	Starter N	0.817	0.778	0.780	0.840	0.734	0.852	0.957	0.812	0.821	0.808c
	Starter N+P	0.727	0.752	0.877	0.825	0.812	0.808	0.788	0.767	0.795	
Oakville 2019	Starter N	1.124	0.729	0.960	1.075	1.0632	1.158	1.131	1.019	1.032	1.07b
	Starter N+P	1.069	1.309	0.984	0.946	1.102	0.994	1.382	1.044	1.103	
Portage 2019	Starter N	0.638	0.558	0.584	0.540	0.493	0.518	0.564	0.405	0.538	0.555cd
	Starter N+P	0.671	0.530	0.682	0.629	0.492	0.619	0.558	0.401	0.573	
Winkler 2019	Starter N	0.437	0.438	0.440	0.407	0.400	0.443	0.462	0.348	0.422	0.464d
	Starter N+P	0.550	0.437	0.515	0.547	0.480	0.578	0.525	0.420	0.506	
All site-years	Starter N	0.845	0.783	0.771	0.835	0.787	0.806	0.904	0.761	0.812	
	Starter N+P	0.816	0.841	0.840	0.822	0.838	0.803	0.905	0.733	0.825	
Hybrid[a]		0.830AB	0.812B	0.805B	0.828AB	0.813AB	0.804B	0.905A	0.747B		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.6347
Site-year*Fert	5	0.5983
Hybrid	7	0.0002
Site-year*Hybrid	35	0.0556
Fert*Hybrid	7	0.506
Site-year*Fert*Hybrid	35	0.0878
Coeff Var (C.V.)		50.2%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.20 Days from planting to silking as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		Days after planting									
Kane 2018	Starter N	72.0	74.3	73.8	74.0	75.7	74.8	75.5	76.7	74.6cd	73.9c
	Starter N+P	70.7	73.8	72.3	72.5	75.7	74.0	75.7	76.0	73.8d	
Oakville 2018	Starter N	73.3	74.0	73.2	74.2	73.8	73.7	74.3	74.7	73.9d	74.0c
	Starter N+P	73.3	74.0	73.2	73.7	74.3	74.0	75.2	75.5	74.1d	
Portage 2018	Starter N	71.5	71.2	72.0	71.5	72.7	71.5	72.7	72.8	72.0e	70.9d
	Starter N+P	71.3	71.2	69.8	71.8	72.5	72.2	72.5	73.8	71.9e	
Oakville 2019	Starter N	77.0	77.8	77.2	77.2	81.2	78.0	81.0	82.8	79.0ab	79.1a
	Starter N+P	77.6	76.5	78.2	77.2	82.1	78.9	81.3	82.5	79.3ab	
Portage 2019	Starter N	74.0	75.3	74.8	74.7	78.0	75.7	77.0	77.7	75.9c	76.4b
	Starter N+P	74.0	74.5	74.2	75.0	77.8	76.0	77.0	78.3	75.9c	
Winkler 2019	Starter N	78.3	78.2	78.7	77.8	81.0	79.2	80.7	82.0	79.5a	79.0a
	Starter N+P	77.5	77.3	77.8	77.0	79.5	77.7	79.7	81.8	78.6b	
All site-years	Starter N	74.4	75.1	74.9	74.9	77.1	75.5	76.9	77.8	75.8	
	Starter N+P	74.1	74.6	74.3	74.5	77.0	75.4	76.9	78.0	75.6	
Hybrid[a]		74.4D	74.7CD	74.4CD	74.8CD	76.7B	75.2C	76.6B	77.7A		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.035
Site-year*Fert	5	0.0043
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.1846
Site-year*Fert*Hybrid	35	0.5319
Coeff Var (C.V.)		4.2%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.21 Plant height at R2 growth stage as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		cm									
Oakville 2018	Starter N	206	214	200	206	215	198	218	207	208	207c
	Starter N+P	194	213	198	206	220	195	213	211	206	
Portage 2018	Starter N	191	195	191	195	195	192	197	195	194	193d
	Starter N+P	190	195	186	190	195	188	198	195	192	
Portage 2019	Starter N	209	223	217	214	226	210	225	216	217	217b
	Starter N+P	208	220	213	217	227	211	225	218	217	
Oakville 2019	Starter N	219	219	233	231	226	224	230	229	227	228a
	Starter N+P	218	236	225	232	230	232	226	233	229	
Winkler 2019	Starter N	205	220	209	210	218	206	216	204	211	209c
	Starter N+P	201	208	211	210	209	208	211	205	208	
All site-years	Starter N	206	214	210	211	216	206	217	210	211	
	Starter N+P	202	214	207	211	216	207	214	213	211	
Hybrid[a]		204E	214AB	208CD	211BC	216A	206DE	216A	211BC		

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.3385
Site-year*Fert	4	0.2852
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.215
Site-year*Fert*Hybrid	28	0.0667
Coeff Var (C.V.)		7.0%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.22 Corn grain moisture at harvest as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[b]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		g kg^{-1}									
Oakville 2018	Starter N	255	303	264	292	287	292	271	298	283	282a
	Starter N+P	270	305	257	292	282	297	278	300	285	
Portage 2018	Starter N	275	307[a]	271	277	264	251	266	253[a]	271	275a
	Starter N+P	282	255[a]	268	304	274	265	289	298[a]	279	
Oakville 2019	Starter N	222	234	224	225	240	233	241	250	234	236b
	Starter N+P	229	238	227	225	250	239	242	252	238	
Portage 2019	Starter N	236	272	248	263	269	257	268	302	264	267a
	Starter N+P	241	271	253	270	278	272	276	303	271	
Winkler 2019	Starter N	225	220	221	213	231	224	244	228	226	226b
	Starter N+P	224	216	228	216	231	229	234	236	227	
All site-years	Starter N	243	267	246	254	258	251	258	266	255	
	Starter N+P	249	257	247	261	263	260	264	278	259	
Hybrid[b]		246C	262B	246C	258B	261B	254BC	261B	272A		

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0364
Site-year*Fert	4	0.7907
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.0268
Site-year*Fert*Hybrid	28	0.0385
Coeff Var (C.V.)		12.4%

[a]Least square mean values for fertilizer treatments are significantly different for these hybrids at Portage 2019 ($P \leq 0.05$). Refer to Appendix C.13 for letter groupings.

[b]Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Table 2.23 Corn grain yield at harvest as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean [b]	Site Mean [b]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		kg ha^{-1} [a]									
Oakville 2018	Starter N	8137	9451	9175	9429	8684	9367	9928	8675	9106cd	9360bc
	Starter N+P	8163	10588	9209	9926	9569	9378	10304	9778	9614bc	
Portage 2018	Starter N	6634	5703	7111	6458	7045	6251	6092	6533	6478e	8786c
	Starter N+P	5825	6707	5938	6423	5892	5812	6648	5952	6150e	
Oakville 2019	Starter N	10795	10579	11862	9893	10753	9902	12246	10837	10858a	10772a
	Starter N+P	10392	10871	11589	9995	10668	9719	11217	11027	10685a	
Portage 2019	Starter N	7883	8107	9222	8477	7914	8728	9515	9498	8668d	8786c
	Starter N+P	7856	9215	9426	8421	8162	8673	9752	9899	8926cd	
Winkler 2019	Starter N	8554	9145	8271	8991	9481	10418	10703	10485	9506cd	9777b
	Starter N+P	8691	10716	8429	9743	10147	10617	10984	11056	10048ab	
All site-years [b]	Starter N	8401ef	8597def	9128abcde	8650def	8775def	8933bcdef	9697ab	9205abcd	8923	
	Starter N+P	8184f	9619abc	8918cdef	8902cdef	8888cdef	8840cdef	9781a	9542abc	9084	
Hybrid [b]		8292D	9108AB	9005BC	8776CD	8831C	8887C	9739A	9374AB		

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0308
Site-year*Fert	4	0.0025
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.0028
Site-year*Fert*Hybrid	28	0.9723
Coeff Var (C.V.)		19.7%

[a] Grain yield corrected to 155 g kg^{-1}.
[b] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

2.5 Discussion

In both starter fertilizer experiments, accumulated precipitation between planting and the end of August at most site-years ranged from 51% to 72% of the 30-year average. The exception was Winkler 2019 which had close to normal precipitation during that portion of the growing season. Water use by corn is greatest in August when the crop progresses from silking (R1) to milk stage (R3) (Kranz et al. 2008). Given the small amounts of accumulated precipitation, moisture stress probably occurred, limiting overall yields at most site-years. However, soil water reserves were not measured in the spring, so total growing season moisture availability is not known.

In-furrow fertilizer did not reduce stand counts in the experiment to evaluate starter N plus P or the experiment to evaluate starter P alone. Similar to previous studies (Kaiser and Rubin 2013; Kaiser et al. 2016), a moderate rate of APP (22 kg P_2O_5 ha^{-1}) did not reduce corn densities when directly applied in the seed row. In the experiment to evaluate starter N plus P, there was a site-year*hybrid interaction for stand count which was not unexpected as hybrid performance often varies with site specific factors.

Early season biomass increased with application of starter N plus P, but not starter P alone. The difference in response between the experiment to evaluate starter N plus P and P alone is more likely due to site-year specific factors than the N component of the starter fertilizer, as each site-year had over 200 kg ha^{-1} of N broadcast prior to planting. In a previous experiment to evaluate starter fertilizer combinations, Kim et al. (2013) found that early season growth increased with starter P but never with starter N at locations where N was broadcasted. Starter N plus P increased early season biomass by 9%, which was smaller than the increases measured in studies conducted in Minnesota (15%) by Kaiser et al. (2016) and Ontario (34%) by Lauzon and Miller (1997) with in-furrow fertilizer. The lack of early season biomass response in the experiment to evaluate starter P alone also contrasts with a previous study in Manitoba where side-banded P increased early season biomass by 85-110% after canola and 30-38% after soybean (Rogalsky 2017). Hybrids did not differ in early season biomass response to SF in either the starter N plus P or the starter P alone experiment. The increase in early season biomass with starter N plus P across all hybrids is similar to previous studies (Gordon et al. 1997; Buah et al. 1999; Gordon and Pierzynski 2006). Early season biomass response to in-furrow fertilizer did not differ by site-year in either experiment. A lack of early season biomass response in the experiment to evaluate starter P could be the due to the high soil test P (STP) concentrations at most site-years. All site-years had STP concentrations in the very high range except Oakville 2018 and Winkler 2019 which were medium (Table 2.1), according to the Manitoba Soil Fertility Guide (Manitoba 2007). Jokela (1992) found no early season biomass response to SF for soils testing medium to high or higher in available P. However, in the experiment to evaluate starter N plus P, starter fertilizer application increased early season biomass across all site-years, despite all site-years except Roland 2017 having STP concentrations that would be regarded as medium to high or higher. Part of the reason for the early season biomass response to starter N plus P could be the response to starter N. However, as mentioned previously, responses to starter N were not expected because high rates of N were broadcast at all sites prior to planting. Starter fertilizer containing N plus P has been shown to increase early season biomass regardless of STP levels due to the greater positional availability of P from SF (Bundy and Andraski 1999; Bermudez and Mallarino 2002; Kaiser et al. 2005; Roth et al. 2006), especially in cool soils where early season P supply and root growth are slow

(Bermudez and Mallarino 2002; Kaiser et al. 2016). Although starter N plus P increased early season biomass, the increases were not visually detectable as differences in seedling vigour ratings between starter N plus P and the no starter control.

Compared to the treatment without SF, early season tissue P concentration was greater across all hybrids with starter N plus P, whereas starter P alone did not increase P concentration of any hybrid. Our finding that starter N plus P is beneficial across hybrids supports previous research by Gordon et al. (1997) and Gordon and Pierzynski (2006), which when combined, reported SF increased P concentration at V6 for all six hybrids tested. In our starter N plus P experiment, starter fertilizer response differed by site-year as tissue P concentration was greater with starter N plus P compared to the no starter control only at Carberry 2017, Oakville 2017, and Roland 2017, when sites were analyzed individually. Responsiveness to SF at these sites could not be explained by previous crop or STP concentration as the previous crop at each site-year differed and STP concentration ranged from 5 mg kg^{-1} to 38.5 mg kg^{-1}. Previous research suggests that increases in early tissue P concentration with starter fertilizers containing N plus P are poorly related to STP concentration (Kaiser et al. 2005; Roth et al. 2006). In the experiment to evaluate starter P alone, a lack of increase in tissue P concentration with starter fertilizer was surprising given that no supplemental P was applied to the control treatment. These results also contrast with the results of a previous study on corn response to starter P in Manitoba where increases in early season tissue concentration were substantial, ranging from 16-38% after canola and 44-79% after soybean (Rogalsky 2017). Critical tissue P concentration for early season corn between V4-V6 varies widely in the literature, with reported ranges between 3.5 and 5.5 g P kg^{-1} (Barry and Miller 1989; Schulte and Kelling 1991; Mallarino 2013; Stammer and Mallarino 2018). Tissue P concentrations in our experiments were within or higher than this range except for the no starter treatment at Roland 2017 and the starter P treatment at Kane 2018. However, as mentioned before, it is not clear whether tissue P concentrations in our experiment would be rated as deficient or adequate, due to the wide range of literature values for tissue P sufficiency.

Phosphorus uptake generally reflected the results from early biomass and tissue P concentration observations in both experiments. In the experiment to evaluate starter N plus P, SF increased P uptake of all hybrids, similar to previous research (Gordon and Pierzynski 2006). However, the increase in P uptake was significant at only three out of seven individual site-years, and the increases were smaller than the 177% increase reported by Gordon et al. (1997), but closer to the 21% increase reported by Kim et al. (2013) with P-based fertilizers. In the experiment to evaluate starter P alone, early season P uptake did not differ between fertilizer treatments or any fertilizer interactions, reflecting the lack of early season biomass or tissue P concentration response discussed earlier. These results also contrast with a previous study in Manitoba where the increase in corn tissue P uptake with starter P application ranged from 54-248% (Rogalsky 2017).

Starter fertilizer slightly decreased days from planting to silking for all hybrids in both starter fertilizer experiments. The hastening of development across all hybrids with both SF treatments is similar to the results of Lamond et al. (1995), but differs from Gordon et al. (1997) and Gordon and Pierzynski (2006) who found that SF decreased days to silking only for certain hybrids. A lack of hybrid*fertilizer interaction also suggests the increase in rate of development due to SF is consistent across hybrid RMs. This agrees with Kaiser et al. (2016), but not Cromley et al. (2006) who found that later-maturing hybrids have a greater reduction in days required to reach silking with starter fertilizer application than earlier maturing hybrids. Although SF response did not differ by hybrid, advancement in phenological development was observed only at certain site-years. At the site-years where SF treatments advanced development, the reduction in days to silking was small, with the greatest reduction being 1.3 days. A similar one-day reduction in days to silking with the application of in-furrow fertilizer was observed by Kaiser et al. (2016). In Manitoba, Rogalsky (2017) recorded larger reductions in days to silking, with starter P reducing days to silking compared to the no starter control by up to seven days in corn planted after canola and two days in corn planted after soybean. In our study, the reduction in days to silking was preceded by increased early season biomass and P uptake with starter N plus P for Carberry 2017 and Roland 2017, but not for Oakville 2017. In contrast, the starter P alone treatment advanced physiological development only at Winkler 2019 despite the lack of increased early season growth and nutrient uptake for this site-year.

Plant height at R2 decreased slightly (2 cm) with application of starter N plus P, but not starter P alone when averaged across hybrid and site-year. No previous research reporting a decrease in final corn plant size with SF application was found. The effect of SF on plant height did not differ between hybrids in either experiment, but differed with site-year for the starter N plus P experiment. At Carberry 2017, starter N plus P resulted in a 7 cm decrease in plant height despite increased early season biomass, P concentration and P uptake. At the other site-years, plant height was not statistically different between fertilizer treatments despite the overall increase in early season biomass, increased P uptake, and P concentration at Oakville 2018 and Roland 2018 with starter N plus P. Bullock et al. (1993) reported no increase in final plant size even when early season biomass was increased with starter fertilizer. In our experiment to evaluate starter P, plant height was not affected by starter P, reflecting the absence of early season biomass and P uptake response.

At harvest, the grain moisture response to SF differed between the two experiments. Starter N plus P did not affect grain moisture at harvest even though early season growth was increased and days to silking decreased. Similarly, Vetsch and Randall (2002) reported increased early season plant height, but no effect on grain moisture with starter fertilizers containing N plus P compared to the no-starter control. In the experiment to evaluate starter P, the site-year*fertilizer*hybrid interaction indicated that starter P decreased the moisture content of DKC26-28RIB and increased the moisture content of DKC33-78RIB at Portage 2018, with no grain moisture response at other site-years. A reduction in grain moisture content for DKC26-28RIB at harvest with the application of starter P has been observed in previous studies in Manitoba (Rogalsky 2017). In the study by Rogalsky (2017), starter P reduced the grain moisture content of DKC26-28RIB when the previous crop was canola, but not soybean. Further, in a tillage study, Rogalsky (2017) observed a reduction in grain moisture content for DKC26-28RIB with starter P application in two out of four site-years. It is not known why grain moisture at harvest with and without starter P would differ for DKC26-28RIB and DKC33-78RIB compared to other hybrids at Portage 2018, but a possible explanation could be variation due to moisture stress resulting from site-year specific influences. At Portage 2018, the combination of a very coarse-textured soil and growing season precipitation that was 27% lower than the 30-year average resulted in a grain yield that was 3387 kg ha^{-1} lower than the average of the other four site-years. When yield is this low, factors other than hybrid genetics and SF may have an increasing influence on harvest data.

Several studies have reported a hastening of maturity with SF, resulting in reduced days from planting to silking and a reduction of grain moisture at harvest (Bullock et al. 1993; Wolkowski 2000; Kaiser et al. 2016). However, SF may not affect maturity of all hybrids.

Gordon and Pierzynski (2006) reported that starter N plus P reduced days from planting to silking and grain moisture at harvest for only two out of four hybrids tested. In our experiment to evaluate starter P, hybrids differed in response to starter P in terms of grain moisture at harvest, but not days to silking at Portage 2018. Considering the lack of hybrid response to starter P at mid-season, the significant moisture response at harvest was unexpected, especially given that the accumulation of heat units was adequate for hybrids to reach maturity.

Grain yield at harvest increased with the application of starter N plus P and starter P alone, when averaged across site-year and hybrids for each experiment. Grain yield increases due to SF have also been reported in numerous studies (Mascagni and Boquet 1996; Buah et al. 1999; Bundy and Andraski 1999; Bermudez and Mallarino 2002). In contrast to these and our findings, other studies have found that SF did not increase grain yield (Bullock et al. 1993; Kaiser et al. 2005; Roth et al. 2006; Rehm and Lamb 2009; Kaiser et al. 2016). In both of our studies, even though there was an overall yield response to SF across all hybrids, the grain yield response differed across hybrids, with DKC26-28RIB being the only hybrid to have a statistically significant increase with SF compared to the control, when yield response for individual hybrids was analyzed. DKC26-28RIB has previously been shown to be responsive to starter P in Manitoba (Rogalsky 2017). In Rogalsky's tillage study, both the 60 kg P_2O_5 ha^{-1} and the 30 kg P_2O_5 ha^{-1} rate of starter P increased the grain yield of DKC26-28RIB compared to the no starter control. However, in Rogalsky's crop rotation study, only the high rate of P (60 kg P_2O_5 ha^{-1}) led to an increase in yield compared to the control (Rogalsky 2017).

Our observations that hybrids differ in grain yield response to SF are consistent with Teare and Wright (1990), Gordon et al. (1997), and Gordon and Pierzynski (2006), but contrary to Buah et al. (1999). Gordon and Pierzynski (2006) also reported responsive hybrids having reduced days to silking, lower grain moisture, in addition to increased grain yield with SF. DKC26-28RIB did not differ from other hybrids in days to silking reduction with starter P alone, but at Portage 2018 this hybrid had lower grain moisture content with starter P alone compared to the control that did not receive starter P. In a previous study in Manitoba, DKC26-28RIB had reduced days to silking, lower grain moisture, and increased grain yield with application of starter P (Rogalsky 2017). In our study, without application of SF, DKC26-28RIB was among the lowest yielding hybrids. However, when either starter N plus P or P alone were applied, grain yield of DKC26-28RIB was similar to the highest yielding hybrids. Applying SF to responsive early RM hybrids could enable those hybrids to achieve the yields of late RM hybrids and could provide greater profitability, especially in years where CHU accumulation is marginally sufficient or insufficient.

Winkler 2019 was the only individual site-year where grain yield increased with application of starter N plus P and with starter P alone. The consistent yield response to SF at Winkler 2019 could be due to site-year factors such as below optimum STP concentration, canola being the previous crop, and adequate precipitation. Winkler 2019, with an Olsen extractable P level of 14 ppm, was classified as medium residual P level according to the Manitoba Soil Fertility Guide. Yield responses to P-based starter fertilizers are more frequent when STP levels are below optimum for corn production (Jokela 1992; Bermudez and Mallarino; 2004; Wortmann et al. 2006). However, grain yield response to SF can also be poorly related to STP since yield increases are also observed on soil with high STP levels (Lauzon and Miller, 1997; Mascagni and Boquet 1996; Bundy and Andraski, 1999; Bermudez and Mallarino 2004). Similarly, in our experiments, Roland 2017 and Oakville 2018 did not have a statistically significant yield increase due to starter N plus P or starter P alone respectively, despite having

STP concentrations below optimum. The grain yield response to SF at Winkler 2019 may also have been influenced by the previous canola crop. Previous research in Western Canada showed that mycorrhizal populations can be reduced after canola (Bittman et al. 2004) and the likelihood of SF response increases when corn is planted after canola (Bittman et al. 2006). However, no significant yield response to starter N plus P was observed at Roland 2017 despite the corn being planted on canola stubble. Other research in Manitoba has reported that grain yield response to starter P does not differ whether corn is preceded by canola or soybean (Rogalsky 2017). Grain yield response to starter fertilizer can also depend on water availability (Wortman et al. 2006). Winkler 2019 was the only site-year where rainfall from planting to the end of August was not below the 30-year average. Wortman et al. (2006) found greater probability of grain yield increase with starter fertilizers containing N plus P when soil water deficits were less severe. Adequate to above average rainfall at Winkler 2019 could have removed soil moisture deficit as a limiting factor affecting corn response to starter fertilizer.

2.6 Conclusions

Application of starter fertilizers containing N plus P or P alone is generally beneficial for corn production. Across all hybrids, both starter N plus P and P alone resulted in overall increases in grain yield. However, starter fertilizer appears to be more beneficial for some hybrids than others. When starter fertilizer responses were evaluated for individual hybrids, starter N plus P or P alone increased grain yield of only one hybrid, DKC26-28RIB.

In addition, hybrids differed in grain moisture response to the starter P alone treatment at one site-year. At Portage 2018, grain moisture content at harvest was lower for DKC26-28RIB and higher for DKC33-78RIB with starter P compared to the control. Although hybrids differed in response to SF at harvest, hybrids did not respond differently earlier in the growing season. Starter N plus P increased early season biomass, P concentration and P uptake and decreased time to silking and final plant height of all hybrids. Starter P alone did not affect early season biomass, P concentration, P uptake or final plant height of any hybrid, but resulted in a shortened time to silking for all hybrids. Benefits of SF also depend on site and year influences. Starter N plus P increased P uptake and P concentration, and decreased time to silking at three out of seven site-years and increased grain yield at harvest at one out of four site-years. However, early season biomass was increased across site-years. Starter P alone decreased days to silking and increased grain yield at one site-year. Results of this study show the use of SF generally increases early season growth and hastens phenological development across hybrids. However, the effect of SF on grain yield varied with hybrid. Since the use of SF is ultimately about profitability, it would be valuable for corn growers to know whether the hybrids grown on their farm are likely to have a grain yield response to SF before applying SF or investing in SF application equipment. Furthermore, plant breeding companies should know that hybrids can differ in SF response in order to set up and interpret the results of their field trails to appropriately assess product performance due to genetic potential versus SF response. Characterizing hybrids by responsiveness to SF also enables informed fertilization recommendations for growers, so that the performance of a hybrid in the growers' field will meet expectations.

3. Relationship between corn seedling root measurements and phenotypic response to starter nitrogen plus phosphorus and starter phosphorus

3.1 Abstract

The field studies (Chapter 2) examining eight corn hybrids (*Zea mays* L.) showed that hybrids differed in response to both starter N plus P fertilizer and starter P fertilizer alone. The objectives of this study were to measure early seedling root growth of those eight hybrids and determine if early root growth measurements were related to starter fertilizer responses measured in the field studies. Eight hybrids were grown in germination pouches containing blue blotter paper in a controlled environment at 11.5/8.5°C (16 h/8 h) without supplemental nutrients or light. After 11 days, digital images were captured, then analyzed using SmartRoot image analysis software to measure root length and surface area. Pearson's correlation coefficients for percent increase in grain yield due to starter N plus P and root length (r=-0.82) and root surface area (r=-0.82) were significant, whereas percent increase in early season biomass, P concentration, P uptake, seedling vigour, days to flowering, plant height and grain moisture at harvest were not correlated to root measurements. There was no significant correlation between any measured phenotypic increase due to starter P alone and root length or surface area. Percent increase in grain yield due to starter N plus P was inversely related to root length (R^2=0.68) and surface area (R^2=0.67) suggesting hybrids with smaller early seedling root systems are more likely to have a positive grain yield response to starter fertilizers containing N and P. Measuring root length and surface area of corn seedlings grown on germination paper for 11 days may be a fast and convenient method to screen whether hybrids are likely to benefit from starter fertilizer application.

3.2 Introduction

Starter fertilizer (SF) typically containing N and P, placed directly in-furrow or banded near the seed (5 cm to the side and 5 cm below) is a common practice for corn (*Zea mays* L.) growers. Field experiments (Chapter 2) showed that SF increased early season biomass, P uptake, tissue P concentration, and reduced days to reach the silking stage. However, even though there was an overall increase in grain yield for SF, when the interaction between hybrid and SF was analyzed, SF increased grain yield for DKC26-28RIB, but not the other seven hybrids. Differential responses to SF have been reported in previous studies with corn hybrids (Teare and Wright 1990; Gordon et al. 1997; Gordon and Pierzynski 2006). Differences in response have been attributed to growth response to temperature and morphological differences in root characteristics (Rhoads and Wright 1998; Gordon and Pierzynski 2006).

The corn root system consists of seminal roots, originating from the seed, that are important for seedling vigour and nodal roots that originate from the shoot and comprise the majority of the adult root system (Hochholdinger et al. 2018; Hochholdinger et al. 2004; Nielsen 2020). In addition, root hairs that originate from root epidermal cells increase the surface area of both seminal and nodal roots (Clarkson 1985; Zhu et al. 2010). Combined, the root system is responsible for anchorage and the acquisition of water and nutrients (Mengel and Barber 1974; Feldman 1994).

The rooting characteristics of corn vary between genotypes. Nielsen and Barber (1978) evaluated 12 inbreds and found a three-fold variation in root weight at 16 days after planting. Further, Costa et al. (2002) observed up to a three-fold variation in root length and surface area between corn hybrids at the silking stage. In addition to genetic differences, corn root morphology and rate of growth is influenced by temperature (Kasper and Bland 1992; Costa et al. 2002). Cold temperatures reduce early season vegetative biomass, root length, root weight and root volume (Mackay and Barber 1984; Chassot and Richner 2002; Wijewardana et al. 2015). Reduced root growth can limit the plant's ability to take up nutrients, particularly nutrients such as P, with limited solubility and diffusion, especially at low temperatures (Mackay and Barber 1984; Sheppard and Racz 1984). The effect of cold temperatures on corn root growth varies with genotype (Hund et al. 2007; Hund et al. 2008). Evaluating 33 corn hybrids at three temperature regimes, Wijewardana et al. (2015) identified cold-tolerant hybrids that had greater shoot and root growth at lower temperatures. The ability of certain genotypes to form a large root system, even at cool temperatures allows for fast soil exploration and better nutrient supply (Hund et al. 2008) which may limit response to SF (Gordon and Pierzynski 2006). In a field study, Gordon and Pierzynski (2006) found greater total root count and rooting depth at V6 in hybrids that did not have a grain yield increase or advanced maturity as a result of SF compared to responsive hybrids. In two glasshouse experiments, Rhoads and Wright (1998) reported greater root weight at 33 and 41 days after planting for a hybrid that was previously determined to be non-responsive to SF, compared to a responsive hybrid.

Various methods are used to study root growth in both field and controlled environments including excavation, profile wall, labelling and container methods (Bohm 1979). A fast and compact method to study seedling root growth in a controlled environment is to grow seeds in germination pouches followed by digital image capture and analysis (Hund et al. 2009).

The objectives of this study were to evaluate early seedling root length and root surface area of eight corn hybrids in a controlled environment and relate these rooting characteristics to phenotypic response to starter N plus P and P alone from field studies (Chapter 2). We hypothesized that the eight hybrids would differ in root measurements and that hybrids with smaller phenotypic response to starter fertilizer would have greater root length and surface area.

3.3 Materials and Methods

3.3.1. Experimental design

An indoor experiment was conducted using seed germination pouches in a refrigerator without light at 11.5/8.5°C (16hr/8hr) to simulate typical early spring soil temperatures from the field experiments (Appendix B.11). High-contrast blue blotter pouches (blue germination paper inside a plastic pouch) that were used to germinate the seeds (Mega International, Newport, MN) measured 18 cm high by 16.5 cm wide and were placed on stands with slots to keep the pouches upright (Mega International, Newport, MN).

Eight corn hybrids were evaluated in the indoor experiment, using the same hybrids as in the field experiment described in Chapter 2. All corn seeds were treated with both insecticides and fungicides (Appendix A.1.). Three seeds of each hybrid were evenly spaced in each germination pouch. Before placing in a refrigerator, 45 mL of distilled water were added to each pouch. Each stand was one replicate as it contained all eight hybrids, randomly assigned to each slot. Stands were randomized before placing into the refrigerator to achieve a completely randomized experimental design. The experiment was conducted twice. The first run had four replicates per hybrid while the second run had five replicates per hybrid. All means for the indoor experiment are reported for both runs (i.e., 9 replicates in total).

3.3.2. Root Measurements

After 11 days, the germination pouches were removed from the refrigerator. The germination paper, along with the seeds were removed from the pouch and placed under a Nikon COOLPIX L820 camera (Nikon Corporation, Tokyo, Japan) mounted in a fixed position. Each germination paper was placed in the same position, along with a ruler, to ensure the digital images captured were from the same height and angle (Fig. 3.1). Images were processed with the SmartRoot plugin (Lobert et al. 2011) in the imaging program ImageJ (Schneider et al. 2012) to measure root length and surface area. Seedling root length and surface area per seedling were calculated by dividing the total from the number of seedlings per germination paper.

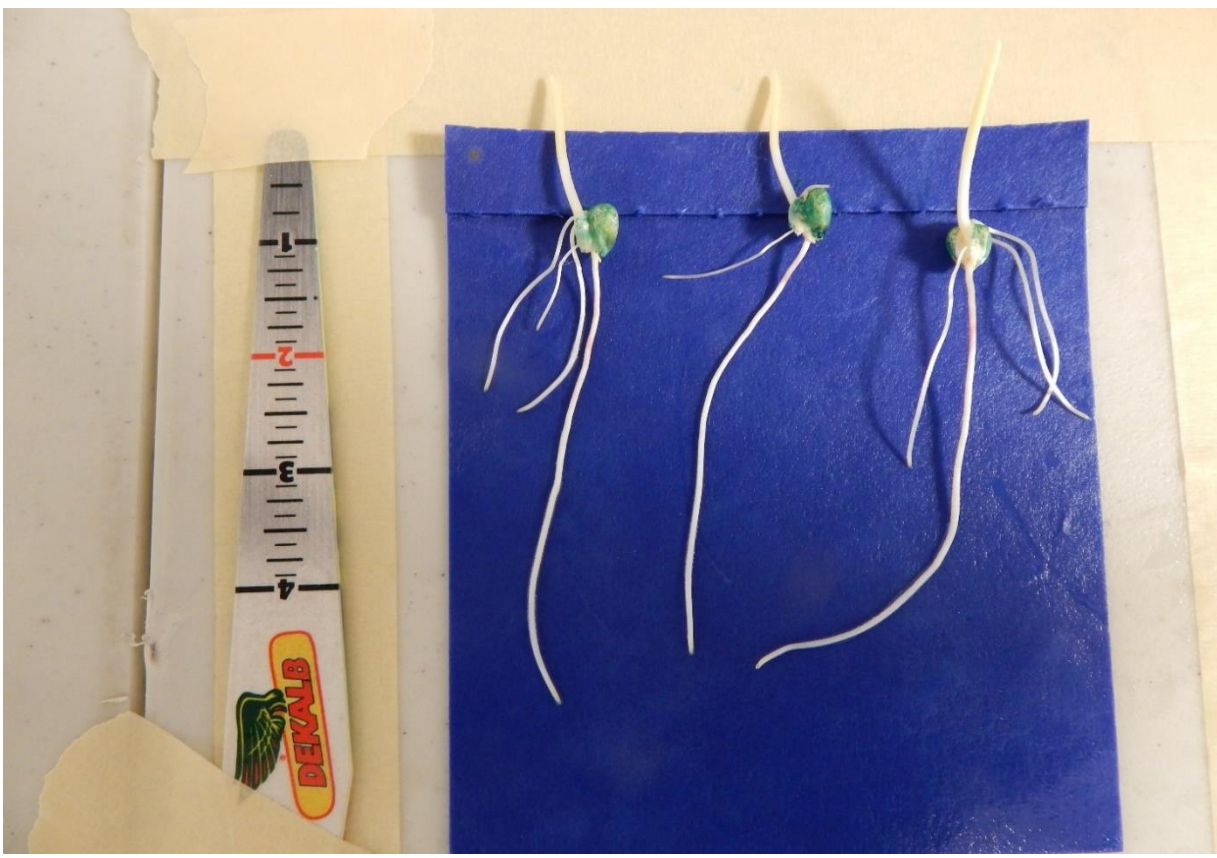

Figure 3.1. Digital image of DKC23-17RIB 11 days after imbibition.

Seeds that did not germinate were excluded from the calculation. DKC30-19RIB was excluded from the results due to poor germination. Therefore, results are reported for only seven of the eight hybrids that were used in the field study.

3.3.3. Statistical analysis

Root data were analyzed using the Proc Mixed procedure and tested for normality of residuals using the Proc Univariate procedure and Shapiro-Wilk statistics in SAS 9.4. Results were considered significant when $P \leq 0.05$. The Tukey-Kramer test was used to assign letter groupings to treatment means. In the statistical model, hybrid was treated as a fixed effect.

Field studies in this research project (Chapter 2) provided the data sets used to assess the relationship between root length and surface area to corn response to starter N plus P and starter P alone. Changes in measured phenotype traits due to application of starter N plus P and starter P alone for each individual hybrid, averaged across all site-years, are summarized in Table 3.1 and Table 3.2 respectively. Both the starter N plus P and starter P alone studies evaluated eight corn hybrids, each planted at eight site-years. Across all hybrids as a group, starter N plus P increased early season biomass, tissue P concentration, P uptake, and yield and decreased plant height as well as time required to reach silking. Starter P alone increased yield and moisture content at harvest and decreased time required to reach silking across all hybrids. However, individual hybrids differed in grain yield response to both starter N plus P and starter P alone. Hybrids also differed in response to starter P alone for grain moisture at harvest at one site-year.

The Proc Corr procedure in SAS was used to compare root length and surface area to corn phenotypic response (% increase in biomass, P concentration, P uptake, days to pollen shed, days to silk, grain moisture at harvest and grain yield) to starter N plus P and starter P alone.

Root length and surface area were also compared to the thousand kernel weight of the seed source used in this experiment. The Proc Reg procedure was used to regress root length and surface area with phenotypic responses to starter N plus P and starter P alone that had significant correlations below the P=0.05 significance threshold in the Proc Corr procedure.

Table 3.1 Phenotypic response of corn hybrids to starter nitrogen plus phosphorus in the field experiment.

Hybrid	Early season biomass	Tissue P concentration	Above ground P uptake	Seedling vigour	Days to 50% pollen shed	Days to 50% silk	Final plant height	Grain moisture	Grain yield
	Percent increase above the control treatment								
DKC23-17RIB	12.8	8.5	21.6	0.2	-1.2	-0.9	-2.3	0.4	1.4
DKC26-28RIB	17.0	18.5	39.5	3.9	-1.4	-1.4	-0.9	-1.7	8.4
DKC26-40RIB	5.7	8.2	13.5	-4.3	-1.2	-1.0	0.0	1.3	0.8
DKC27-55RIB	5.3	12.4	21.0	18.6	-1.2	-1.2	-0.5	-1.3	4.3
DKC30-07RIB	8.8	11.9	21.4	-6.7	-1.0	-0.9	-0.9	0.0	3.5
DKC32-12RIB	12.4	13.6	27.8	12.1	-0.8	-0.7	-1.8	-2.0	-0.4
DKC33-78RIB	8.3	13.0	23.9	2.6	-0.2	0.0	-0.9	-0.4	3.7

Table 3.2 Phenotypic response of corn hybrids to starter phosphorus alone in the field experiment.

Hybrid	Early season biomass	Tissue P concentration	Above ground P uptake	Seedling vigour	Days to 50% pollen shed	Days to 50% silk	Final plant height	Grain moisture	Grain yield
	Percent increase above the control treatment								
DKC23-17RIB	1.9	-4.4	-3.4	-3.1	-0.5	-0.4	-1.9	2.5	-2.6
DKC26-28RIB	11.0	-4.0	7.4	1.2	-0.8	-0.7	0.0	-3.7	11.9
DKC26-40RIB	11.5	-1.3	8.9	0.4	-1.1	-0.8	-1.4	0.4	-2.3
DKC27-55RIB	3.5	-4.4	-1.6	4.7	-0.5	-0.5	0.0	2.8	2.9
DKC30-07RIB	7.3	0.2	6.5	0.2	0.1	-0.1	0.0	1.9	1.3
DKC32-12RIB	1.6	0.5	0.1	-4.8	-0.4	0.0	-1.3	2.3	0.9
DKC33-78RIB	-0.6	-3.3	-3.7	6.8	0.0	0.3	1.4	4.5	3.7

3.4. Results

3.4.1. Seedling root length and surface area

Eleven days after imbibition, radicle and seminal roots were present. The SmartRoot plugin (Lobert et al. 2011) was able to distinguish and measure root length and surface area of both root types. However, the digital image did not provide enough resolution for root hair length and root hair surface area to be determined. Analysis of variance indicated that both root length and surface area differed among hybrids at eleven days after imbibition (Table 3.3). Root length and surface area were not correlated with thousand kernel weight, using the *P*=0.05 significance threshold (Table 3.4).

Table 3.3 Root length and root area per seedling for seven corn hybrids, 11 days after imbibition.

Hybrid	Root length (cm)[a]	Root surface area (cm^2)[a]
DKC23-17RIB	27.4a	16.6a
DKC26-28RIB	15.8c	10.0c
DKC26-40RIB	21.1b	12.9b
DKC27-55RIB	18.7bc	12.0bc
DKC30-07RIB	22.7ab	14.1ab
DKC32-12RIB	27.3a	16.6a
DKC33-78RIB	18.3c	11.4c

[a] Within the columns for root length and root surface area, across all hybrids, least square mean values followed by the same letters are not significantly different ($P \leq 0.05$).

Table 3.4 Pearson's correlation coefficients (*r*) for corn seedling root measurements and mean thousand kernel weight of each corn hybrid seed source. Sample size (*N*) = 7.

	Root length (cm)	Root surface area (cm^2)
Thousand kernel weight (g)	-0.20 n.s.[a]	-0.21 n.s.[a]

[a] n.s. = not significant at $P \leq 0.05$.

3.4.2. Seedling root measurements and phenotypic response to starter fertilizers

When root length and surface area were compared to phenotypic response to starter N plus P, the Pearson's correlation coefficients for the relationships between percent increase in grain yield and root length (r=-0.82) and root surface area (r=-0.82) were the only significant correlations, using the P=0.05 significance threshold (Table 3.5). There was no significant correlation between root length or surface area with percent increase in early season biomass, P concentration, P uptake, seedling vigour, days to flowering, plant height, or grain moisture response to starter N plus P. Root length and surface area were then regressed against percent increase in grain yield due to starter N plus P, resulting in coefficient of determination (R^2) values of 0.68 and 0.67, respectively (Fig. 3.2), with P values of 0.023 and 0.025, respectively. The R^2 values and negative slope, indicate an inverse relationship between percent increase in grain yield due to starter N plus P and both seedling root length and surface area.

In the correlation analysis for phenotypic response to starter P alone and root measurements after 11 days, the Pearson's correlation coefficients for percent increase in seedling vigour and root length (r=-0.82) and root surface area (r=-0.80) were the only significant correlations, using the P=0.05 significance threshold (Table 3.6). However, there were no evidence of an overall fertilizer effect (P=0.8469) or a fertilizer*hybrid interaction (P=0.6034) on seedling vigour from the analysis of variance in the field experiment. The analysis of variance may not be sensitive enough to detect the consistent but small effect of starter P on seedling vigour. There were no significant correlations between root length or surface area and percent increase in early season biomass, P concentration, P uptake, days to flowering, plant height grain moisture or grain yield response to starter P alone. Root length and surface area were then regressed against percent increase in seedling vigour due to starter P alone, resulting in coefficient of determination (R^2) values of 0.67 and 0.65 respectively (Fig. 3.3) with P values of 0.0247 and 0.0292, respectively. The R^2 values and negative slope indicate an inverse relationship between percent increase in seedling vigour due to starter P alone and both seedling root length and surface area.

Table 3.5 Pearson's correlation coefficients for corn seedling root measurements in the indoor experiment and phenotypic response to starter nitrogen plus phosphorus in the field experiment. Sample size (*N*) = 7.

	Root length (cm)	Root surface area (cm^2)
	r	
Root surface area (cm^2)	0.99*	-
Early season biomass increase at V4-V6 (% increase over control)	0.08	0.06
Tissue P concentration increase at V4-V6 (% increase over control)	-0.55	-0.55
Above ground P uptake increase at V4-V6 (% increase over control)	-0.33	-0.33
Seedling vigour at V5-V6 (% increase over control)	-0.08	-0.05
Days to 50% pollen shed (% increase over control)	0.02	0.02
Days to 50% silk (% increase over control)	0.16	0.15
Final plant height (% increase over control)	-0.71	-0.71
Grain moisture (% increase over control)	0.16	0.13
Absolute grain yield (kg ha^{-1})	-0.08	-0.10
Grain yield increase (% increase over the control)	-0.82*	-0.82*

*Significant at $P \leq 0.05$.

Table 3.6 Pearson's correlation coefficients for corn seedling root measurements in the indoor experiment and phenotypic response to starter phosphorus alone in the field experiment. Sample size (*N*) = 7.

	Root length (cm)	Root surface area (cm^2)
	r	
Root surface area (cm^2)	0.99*	-
Early season biomass increase at V4-V6 (% increase over control)	-0.39	-0.41
Tissue P concentration increase at V4-V6 (% increase over control)	0.44	0.43
Above ground P uptake increase at V4-V6 (% increase over control)	-0.29	-0.31
Seedling vigour at V5-V6 (% increase over control)	-0.82*	-0.80*
Days to 50% pollen shed (% increase over control)	0.12	0.15
Days to 50% silk (% increase over control)	0.24	0.24
Final plant height (% increase over control)	-0.73	-0.72
Grain moisture (% increase over control)	0.40	0.42
Absolute grain yield (kg ha^{-1})	-0.11	-0.12
Grain yield increase (% increase over the control)	-0.74	-0.74

*Significant at $P \leq 0.05$.

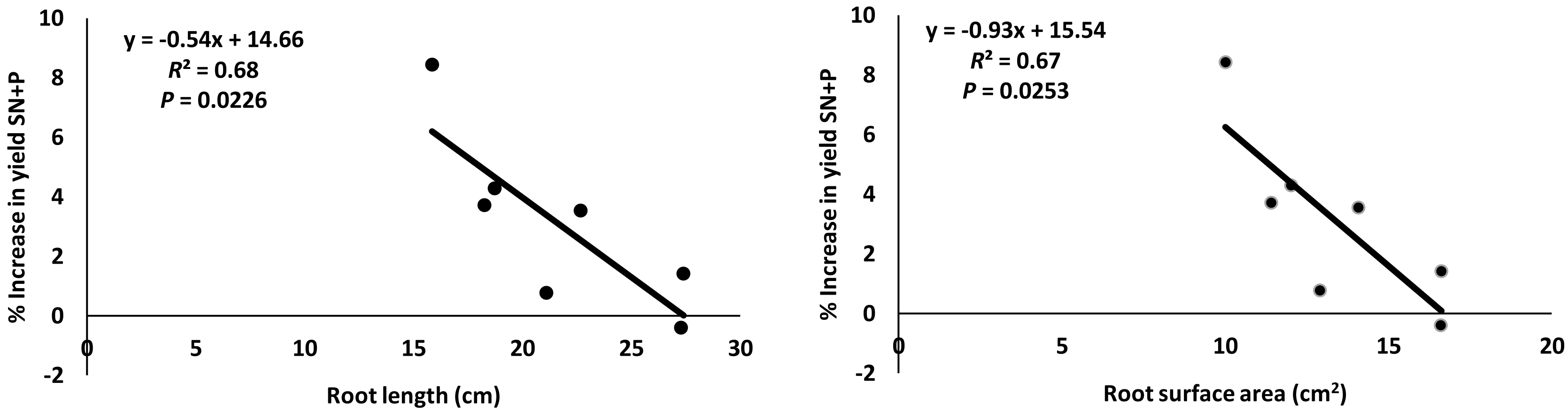

Figure 3.2. Seedling root length and root surface area regressed against percent grain yield increase due to starter nitrogen plus phosphorus.

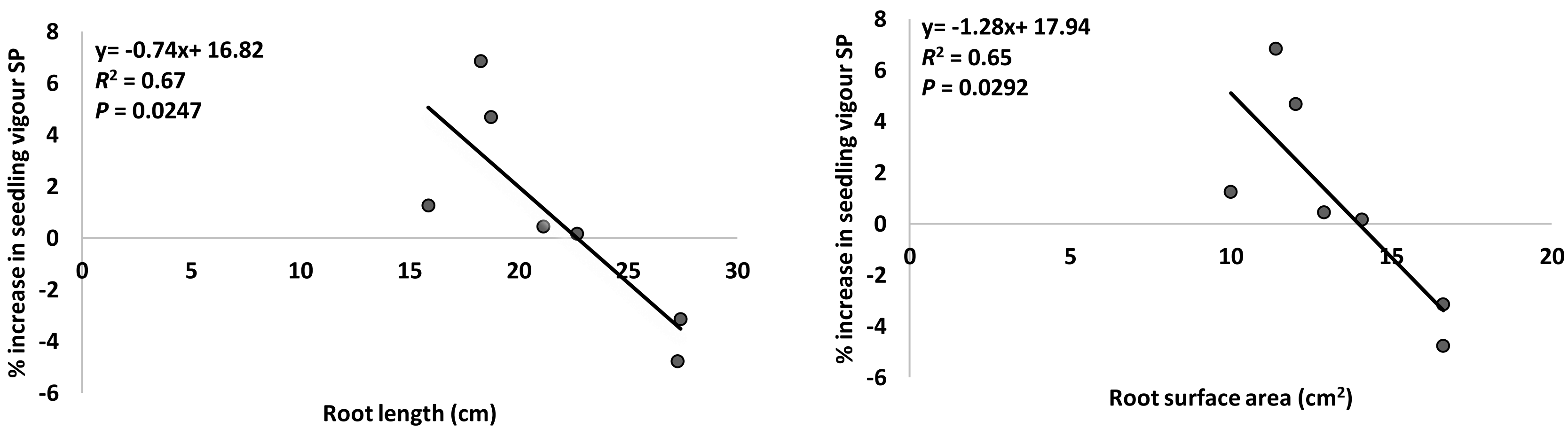

Figure 3.3. Seedling root length and root surface area regressed against percent seedling vigour increase due to starter phosphorus alone.

3.5 Discussion

Differences in root length and surface area between hybrids were expected. Numerous studies have shown genotypic variation in root characteristics (Nielsen and Barber 1978; Pan et al. 1985; Costa et al. 2002). In addition to contributions to root characteristics from genetics, seed size can also play a factor. El-Abady (2015) examined different sized seeds (determined by hand-screens) of the same hybrid and found that root length at 15 days increased with seed size. However, in our experiment, seed size determined by thousand kernel weight for each hybrid was not correlated to root length and surface area at 11 days after imbibition (Table 3.2). Therefore, seed size was not a significant factor that influenced root growth in our experiment.

The inverse relationships between root length or surface area and grain yield response to starter N plus P suggest that early seedling root length and surface area could be an indicator of corn hybrid yield response to that type of starter fertilizer. In addition, root length and surface area of DKC26-28RIB, the only hybrid to have a significant grain yield response to either starter N plus P or starter P alone, were numerically lower than the other seven hybrids and were statistically lower than four of the other hybrids. Previous studies have indicated grain yield response to SF may be attributed to differences in early season root growth of hybrids (Rhoads and Wright 1998; Gordon and Pierzynski 2006). Rhoads and Wright (1998) reported less root weight in a grain yield-responsive hybrid at 33 and 41 days after planting compared to a hybrid that did not have a positive grain yield response to starter N plus P. Gordon and Pierzynski (2006) evaluated rooting characteristics at V6 and reported that responsive hybrids had fewer root counts and shallower rooting depth than responsive hybrids, when no starter fertilizer was applied. Although the previous studies did not measure root length and area, the addition of our results support the idea that root morphological differences between corn hybrids may impact grain yield responsiveness to SF.

There were no significant correlations between root length or surface area and early season biomass, P concentration, P uptake, seedling vigour, days to flowering, plant height, or grain moisture at harvest response to starter N plus P. This was expected, as grain yield was the only observation where the analysis of variance identified a hybrid*fertilizer interaction. However, Gordon and Pierzynski (2006) found that in addition to having a positive yield response, hybrids with lower root counts and less rooting depth also had greater increases in P uptake, reductions in days to maturity, and reductions in grain moisture at harvest when SF was applied.

In the correlation analysis for phenotypic response to starter P alone, the inverse relationships between seedling vigour increase and root length or surface area suggest that hybrids with less root length and surface area may have greater early season growth response to starter P alone. However, there was no evidence of a fertilizer*hybrid interaction on seedling vigour in the field experiment (P=0.6034). Therefore, the correlation between root length and surface area and seedling vigour response to SP in this experiment may not have a practical impact in the field environment.

Root length and surface area were not correlated with any other phenotypic response to starter P alone from the field experiment. The absence of correlation between seedling root measurements and percent increase in early season biomass, P concentration, P uptake, days to flowering, and plant height is consistent with the lack of hybrid*fertilizer interaction in the analysis of variance of the mentioned characteristics in the field study. However, the field experiment indicated that these hybrids differed in grain moisture and yield response to starter P alone. Rhoads and Wright (1998) determined that root growth was less for a hybrid that had a positive grain yield response to starter N plus P compared to a hybrid that was non-responsive. Rhoads and Wright (1998) suggest that differences in root growth between hybrids are more likely to influence response to starter N than starter P alone as both hybrids in their experiment responded to starter P alone, but only the hybrid with less root growth responded to starter N. In our experiment, root length and surface were correlated with yield response to starter N plus P, but not P alone, a potentially significant observation since most commercial P fertilizers also contain N. However, we cannot state whether root morphology is more indicative of a hybrid's response to starter N plus P versus P alone because the field experiments to evaluate response to starter N plus P and P alone were conducted on different sites and years.

3.6 Conclusions

Early corn seedling root length and surface area may be used as a predictor of grain yield response to starter fertilizers containing nitrogen and phosphorus. Percent increase in grain yield with starter N plus P over the control was inversely related to seedling root measurements. Although percent increase in grain yield from starter P alone was not correlated to root measurements, that lack of correlation could be due to variation in site-year influences in the field study and not root measurements being a better predictor of grain yield response to starter N plus P than starter P alone. Nevertheless, a quick method of screening hybrids for likelihood of grain yield response to SF before planting could be to measure root length or surface area of seedlings 11 days after imbibition.

4. SYNTHESIS

4.1. Contribution to Knowledge

Corn production in Western Canada is likely to continue increasing. With the expansion of corn acreage, the interest in applying starter fertilizer to increase early season vigour, advance maturity, and achieve greater yields will also grow. In a recent survey of 100 corn growers in Manitoba, 52% reported the use of starter fertilizer (Heard and Cott 2018). Therefore, it is important to understand how corn responds to starter fertilizer.

Application of starter N plus P should be generally recommended for corn production in Manitoba. Our field study showed that placing nitrogen plus phosphorus in-furrow was beneficial to corn production due to increased P uptake, greater early-season biomass, accelerated maturity, and increased grain yield when averaged across site-years and hybrids. In-furrow applications of starter P alone also accelerated maturity and increased grain yield when averaged across site-years and hybrids. However, since most commercial sources of P fertilizer in Manitoba are ammoniated phosphates, the benefit of starter P alone may be a moot point from a practical perspective.

As expected, the acceleration in maturity and the increase in grain yield due to starter fertilizer was greater at some site-years than others. However, the response to both types of starter fertilizer also differed between hybrids. The influence of hybrid selection and site-year factors on starter fertilizer response is important for growers and agronomists because starter fertilizer recommendations should ultimately be tailored to each field and hybrid planted. In the field studies, both starter fertilizers increased grain yield overall, but the benefit was mainly due to the response of DKC26-28RIB, the only hybrid with a significant yield increase. It may be of value for growers to conduct on-farm trials to determine if starter fertilizer is beneficial for all or some of the hybrids they grow since the use of starter fertilizer has an economic and time cost. However, given the variability in starter fertilizer response to site and year, these types of trials may not generate reliable information fast enough to keep up with the pace of phasing out old hybrids and introducing new hybrids.

Another option that may help starter fertilizer use decisions could be to screen hybrids for likelihood of response prior to planting. The controlled environment study found that root length and root surface area at 11 days after ambition were inversely related to percent increase in grain yield with starter N plus P over the control. The germination pouches used in this study are commercially available and provide a fast and easy way for root measurements to be taken. Applying starter fertilizer to the hybrids with the smallest root systems in their early seedling stage could be an option of increasing the likelihood of a profitable response from starter fertilizer use.

The differential response of hybrids to starter fertilizer should also be of interest to corn breeding programs and seed companies. Characterizing hybrids as either responsive or non-responsive to starter fertilizer allows seed companies to acquire information about the robustness of hybrid performance and the appropriate agronomic practices to maximize customer satisfaction for each hybrid. Also, a seed company’s decision about whether to use starter fertilizer in their breeding program may inadvertently favour certain hybrids. In the field study, DKC26-28RIB was among the lowest yielding hybrids when no starter fertilizer was applied, but with starter fertilizer application, DKC26-28RIB was among the highest yielding hybrids. Breeding programs that use starter fertilizer may be favouring hybrids that are positive responders whereas programs that do not use starter fertilizer may benefit robust hybrids that perform well regardless of whether or not starter fertilizer is applied.

4.2. Future Studies

We observed inverse relationships between root length and surface area at 11 days after imbibition and percent grain yield increase with starter nitrogen plus phosphorus. Future studies should consider evaluating root measurements at different time intervals. Eleven-day old seedlings primarily depend on kernel reserves for nutrition and have only seminal roots present. As the seedling develops, nodal roots form and externally sourced nutrients become more important for growth. Therefore, older seedlings should also be evaluated to see if the relationship between root measurements and percent grain yield increase with starter nitrogen plus phosphorus or starter P alone is stronger.

The field study evaluated only eight hybrids so there is opportunity to expand and assess starter fertilizer response for more hybrids. However, as mentioned previously, the commercial lifespan of hybrids is usually short. At the time of writing, DKC26-28RIB is no longer available. Therefore, future studies may find greater value in evaluating starter fertilizer response of the parental inbred lines that make up commercial hybrids. Le Marié et al. (2019) reported high heritability of root traits in corn. Our controlled environment study combined with previous literature indicates root length and surface area are good predictors of starter fertilizer response. If differential starter fertilizer response is identified in inbreds and is heritable, there is potential to classify hybrids as responsive or non-responsive to starter fertilizer at an earlier stage of breeding new hybrids.

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6. APPENDICES

Appendix A

Details for Materials and Methods (Chapter 2)

Appendix A.1. Corn seed treatment products used in the field and indoor experiments to evaluate starter fertilizer (Chapter 2 and Chapter 3).

Hybrid	Treatment Package
DKC23-17RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250
DKC26-28RIB	Ipconazole, Metalaxyl, Trifloxystrobin, Clothianidin 250
DKC27-40RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250
DKC27-55RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250
DKC30-07RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250
DKC30-19RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250
DKC32-12RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250
DKC33-78RIB	Prothioconazole, Metalaxyl, Fluoxastrobin, Clothianidin 250

Appendix A.2. Corn herbicide application dates, products and rates for the experiments to evaluate starter nitrogen plus phosphorus and starter phosphorus alone (Chapter 2).

Site-year	Herbicide application		
	Date of application	Product	Rate
			L ha^{-1}
Carberry 2017	2017 May 23	Banvel II (480 g a.e./L Dicamba formulated as a solution of a diglycolamine salt)	0.29
		Elim EP (25% rimsulphuron formulated as a wettable granule)	60[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
	2017 June 14	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
Oakville 2017	2017 May 23	Banvel II (480 g a.e./L Dicamba formulated as a solution of a diglycolamine salt)	0.29
		Elim EP (25% rimsulphuron formulated as a wettable granule)	60[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
	2017 June 13	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
Roland 2017	2017 May 18	Banvel II (480 g a.e./L Dicamba formulated as a solution of a diglycolamine salt)	0.29
		Elim EP (25% rimsulphuron formulated as a wettable granule)	60[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
	2017 June 12	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
Winnipeg 2017	2017 May 15	Banvel II (480 g a.e./L Dicamba formulated as a solution of a diglycolamine salt)	0.29
		Elim EP (25% rimsulphuron formulated as a wettable granule)	60[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
	2017 June 9	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5

[a]Measured in g ha^{-1}

Appendix A.2. Corn herbicide application dates, products and rates for the experiments to evaluate starter nitrogen plus phosphorus and starter phosphorus alone (Chapter 2).

Site-year	Herbicide application		
	Application date	Product	Rate
			L ha^{-1}
Homewood 2018	2018 May 10	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
Kane 2018	2018 May 10	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
	2018 June 11	Lontrel 360 (360 g/L clopyralid formulated as a solution)	0.5
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
Oakville 2018	2018 May 11	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
	2018 June 11	Pardner (280 g/L bromoxynil formulated as an emusifiable concentrate	1
		Ultim 75DF (37.5% rimsulphuron and 37.5% nicosulphuron formulated as a water dispersable granule)	33.7[a]
		Agral 90 surfactant	0.4
	2018 June 30	Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
Portage 2018	2018 May 11	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
	2018 June 12	Pardner (280 g/L bromoxynil formulated as an emusifiable concentrate	1
		Ultim 75DF (37.5% rimsulphuron and 37.5% nicosulphuron formulated as a water dispersible granule)	33.7[a]
		Agral 90 surfactant	0.4
	2018 June 30	Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7

[a]Measured in g ha^{-1}

Appendix A.2. Corn herbicide application dates, products and rates for the experiments to evaluate starter nitrogen plus phosphorus and starter phosphorus alone (Chapter 2).

Site-year	Herbicide application		
	Application date	Product	Rate
			L ha^{-1}
Oakville 2019	2018 May 12	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
	2018 June 12	Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Sortan IS (20% rimsulphuron formulated as a water dispensable granule)	75
	2018 July 3	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
Portage 2019	2018 May 12	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
	2018 June 12	Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Sortan IS (20% rimsulphuron formulated as a water dispersible granule)	75
	2018 July 3	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
Roland 2019	2018 May 17	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
Winkler 2019	2018 May 17	Heat WG (70% saflufenacil formulated as a water soluble granule)	71[a]
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5
	2018 June 17	Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Sortan IS (20% rimsulphuron formulated as a water dispersible granule)	75
	2018 July 6	Armezon (336 g/L topramezone formulated as a suspension)	0.0037
		Roundup Weathermax (540 g a.e./L glyphosate formulated as a solution)	1.7
		Merge surfactant	0.5

[a]Measured in g ha^{-1}

Appendix A.3. Dates for soil sample and crop measurements in the experiment to evaluate in-furrow nitrogen plus phosphorus.

		Site-year							
Time of season	Observation	Carberry 2017	Oakville 2017	Roland 2017	Winnipeg 2017	Oakville 2019	Portage 2019	Roland 2019	Winkler 2019
		Sampling Date							
Pre-season	Soil sample	May 2	May 2	May 4	Apr. 27	Apr. 26	Apr. 26	Apr. 29	Apr. 29
Early Season	Plant count	June 14	June 9	June 9	June 16	June 11	June 11	-[a]	June 12
	Biomass	June 17	June 18	June 19	June 22	June 21	June 20	-[a]	June 20
	Seedling vigour	-[b]	-[b]	-[b]	-[b]	June 25	June 25	-[a]	June 26
Mid-season	Days to silking	July 26	July 26	July 29	July 29	July 23	July 22	-[a]	July 23
		July 29	July 29	Aug. 1	Aug. 1	July 26	July 25	-[a]	July 26
		Aug. 1	Aug. 1	Aug. 5	Aug. 5	July 29	July 29	-[a]	July 29
	Plant Height	Aug. 16	Aug. 15	Aug. 15	Aug. 17	Aug. 12	Aug. 12	-[a]	Aug. 14
Late Season	Moisture	-[c]	Oct. 16	Oct. 13	-[d]	Nov. 13	Oct. 12	-[a]	Nov. 11
	Yield	-[c]	Oct. 16	Oct. 13	-[d]	Nov. 13	Oct. 12	-[a]	Nov. 11

[a] Observation not taken due to poor emergence
[b] Observation not taken in 2017
[c] Observation not taken due to moisture stress
[d] Observation not taken due to wind damage

Appendix A.4. Dates for soil sample and crop measurements in the experiment to evaluate in-furrow phosphorus.

		Site-year							
Time of season	Observation	Homewood 2018	Kane 2018	Oakville 2018	Portage 2018	Oakville 2019	Portage 2019	Roland 2019	Winkler 2019
		Sampling Date							
Pre-season	Soil sample	May 4	May 4	Apr. 30	May 3	Apr. 26	Apr. 26	Apr. 29	Apr. 29
Early Season	Plant count	-[a]	June 10	June 11	June 11	June 11	June 11	-[b]	June 12
	Biomass	-[a]	June 20	June 16	June 16	June 21	June 20	-[b]	June 20
	Seedling vigour	-[a]	June27	June 25	June 25	June 25	June 25	-[b]	June 26
Mid-season	Days to silking	-[a]	July 17	July 74	July 13	July 23	July 22	-[b]	July 23
		-[a]	July 20	July 20	July 16	July 26	July 25	-[b]	July 26
		-[a]	July 23	July 23	July 19	July 29	July 29	-[b]	July 29
	Plant Height	-[a]	Aug. 8	Aug. 7	Aug. 7	Aug. 12	Aug. 12	-[b]	Aug. 14
Late Season	Moisture	-[a]	-[c]	Oct. 18	Sept. 30	Nov. 13	Oct. 12	-[b]	Nov. 11
	Yield	-[a]	-[c]	Oct. 18	Sept. 30	Nov. 13	Oct. 12	-[b]	Nov. 11

[a] Observation not taken due green snap from wind
[b] Observation not taken due to poor emergence
[c] Observation not taken due to moisture stress

Appendix B

Early Season Measurements (Chapter 2)

Appendix B.1. Plant count at V4 as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	plants ha^{-1}							
Carberry 2017	85836 abcd	86277 ab	85173 abcdefg	86443 a	84897 abcdefghi	85339 abcdef	86222 abc	85560 abcde
Oakville 2017	83628 abcdefghijk	83959 abcdefghij	82523 defghijk	84234 abcdefghij	82468 defghijk	82358 efghijk	83959 abcdefghij	84179 abcdefghij
Roland 2017	81696 ijk	83959 abcdefghij	83517 abcdefghijk	83627 abcdefghijk	85835 abcd	85118 abcdefg	85007 abcdefgh	84069 abcdefghij
Winnipeg 2017	84234 abcdefghij	82468 defghijk	82855 cdefghijk	83627 abcdefghijk	84455 abcdefghij	83572 abcdefghijk	82799 defghijk	83296 abcdefghijk
Oakville 2019	83933 abcdefghijk	84566 abcdefghij	83587 abcdefghijk	84514 abcdefghij	84119 abcdefghij	82770 cdefghijk	84313 abcdefghij	84183 abcdefghij
Portage 2019	81916 ghijk	82413 efghijk	81364 jk	82524 defghijk	82579 defghijk	82162 efghijk	82247 efghijk	82910 bcdefghijk
Winkler 2019	8175 1ijk	81364 jk	82854 cdefghijk	82192 efghijk	82082 fghijk	82137 fghijk	82579 defghijk	80426 k

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	0.5443
Site-year*Fert	6	0.4963
Hybrid	7	0.1151
Site-year*Hybrid	42	0.0012
Fert*Hybrid	7	0.5686
Site-year*Fert*Hybrid	42	0.8563
Coeff Var (C.V.)		2.8%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix B.2. Early-season biomass at V4-V6, as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
Carberry 2017	197cdefgh	197cdefgh	185efghi	196cdefgh	199 cdefgh	172fghijk	197cdefgh	186defghi
Oakville 2017	272a	254abc	256abc	253abc	251abc	249abcde	250abcde	259abc
Roland 2017	209abcdefgh	208abcdefgh	205bcdefgh	204bcdefgh	202cdefgh	199 cdefgh	206bcdefgh	211abcdefgh
Winnipeg 2017	269ab	255abc	258abc	258abc	255abc	251abcd	248abcde	248abcde
Oakville 2019	232abcdef	245abcde	219abcdefg	219abcdefg	209abcdefgh	203cdefgh	243abcde	226abcdef
Portage 2019	155ghijl	114jklm	151hijkl	117jklm	109kmn	113jklm	120jklm	93m
Winkler 2019	126ikjklm	109jklm	123hijkl,	110jklm	104lmn	111jklm	111jklm	94lmn

ANOVA	DF	Pr>F
Site-year	6	<.0001
Fert	1	0.0003
Site-year*Fert	6	0.5016
Hybrid	7	<.0001
Site-year*Hybrid	42	0.0063
Fert*Hybrid	7	0.0834
Site-year*Fert*Hybrid	42	0.1108
Coeff Var (C.V.)		33.7%

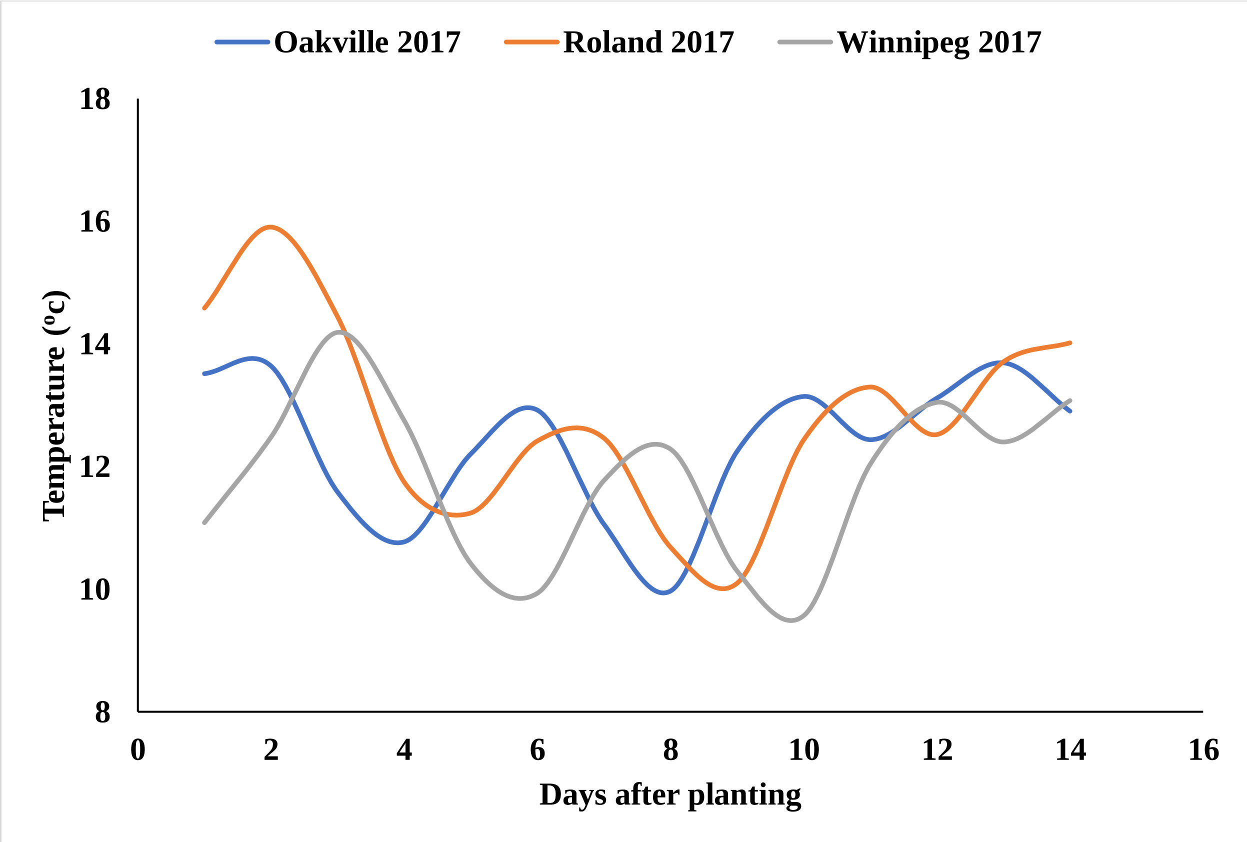
[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix B.3. Seedling vigour at V4-V6, as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	kg ha^{-1}							
Kane 2018	3.2efghijkl	2.7hjkm	4.2bcdefghijk	3.6cdefghijk	3.5cdefghijk	5.0abcdf	2.8ghjkm	4.7abcdefi
Oakville 2018	2.8fghijk	3.2dfghijk	3.4cdefghijk	3.2dfghijk	3.2dfghijkl	5.2abce	3.4cdefghijk	4.2bcdefghijk
Portage 2018	2.8fghijk	2.7ghijk	2.2jn	2.5ijkm	3.3cdefghijk	2.9fghijk	2.2kn	3.4cdefghijk
Oakville 2019	3.2cdefghijk	4.2bcdefghijk	2.9fijklm	3.7cdefghijk	4.9abcdegh	4.9abcdeg	3.6cdefghijk	6.5a
Portage 2019	2.7ghijk	4.0bcdefghijk	2.9fghijk	3.6cdefghijk	3.9bcdefghijk	4.1bcdefghijk	2.7hijk	5.2abcde
Winkler 2019	3.8cdefghijk	4.4abcdefghij	3.7cdefghijk	4.0cdefghijk	4.7abcdefgh	4.4abcdefghij	3.7cdefghijk	6.0ab

ANOVA	DF	*Pr>F*
Site-year	5	0.003
Fert	1	0.8469
Site-year*Fert	5	0.0179
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.6034
Site-year*Fert*Hybrid	35	0.6736
Coeff Var (C.V.)		41.9%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).



Appendix B.11 Average soil temperature from planting to 14 days after planting as measured with Thermochron® DS1921G iButton® temperature logger at 5 cm soil depth (Chapter 2).

Appendix B.12 Visual symptoms of phosphorus deficiency in corn at V3 growth stage at Roland 2017 (Chapter 2).

Appendix C

Mid to Late Season Measurements (Chapter 2)

Appendix C.1. Days from planting to silking as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	g kg^{-1}[b]							
Carberry 2017	70.3x	72.1vw	71.7wx	70.0x	73.8tu	72.5uvw	73.8tu	74.5st
Oakville 2017	74.0tuv	75.6qrst	75.0rst	74.6stu	78.1klmno	76.7npqr	77.9lmnp	78.3jklmno
Roland 2017	77.7lmnpq	78.9ghijklm	78.6hijklmn	78.1lmnp	82.3bcd	80.2efghijk	82.7bc	83.2ab
Winnipeg 2017	79.6fghijkl	82.0bcde	80.5defghi	81.6bcde	85.2a	83.0b	85.0a	85.0a
Oakville 2019	77.6lmnpq	77.0mnpqr	78.0lmno	77.2mnpq	81.9bcde	78.7ghijklmn	81.3bcdef	82.3bcde
Portage 2019	74.2tuv	75.1rst	74.2tuv	75.0rst	78.2klmn	76.2pqrs	77.5lmnpq	78.5hijklmn
Winkler 2019	77.8lmnp	77.9lmnp	78.4iklmno	77.3mnpq	80.8cdefg	78.4iklmno	80.4defghj	81.6bcdef

ANOVA	DF	Pr>F
Site-year	6	<.0001
Fert	1	<.0001
Site-year*Fert	6	0.0157
Hybrid	7	<.0001
Site-year*Hybrid	42	<.0001
Fert*Hybrid	7	0.0590
Site-year*Fert*Hybrid	42	0.2274
Coeff Var (C.V.)		4.9%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

[b] Grain yield corrected to 155 g kg^{-1}.

Appendix C.2. Days from planting to pollen shed as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		Days after planting									
Carberry 2017	No Starter	70.8	72.5	72.3	70.8	74.5	73.2	73.8	73.3	72.7f	72.3d
	Starter N+P	69.0	71.8	70.8	68.7	73.5	72.0	73.7	74.2	71.7g	
Oakville 2017	No Starter	74.5	75.8	75.5	75.0	78.0	76.8	78.0	79.0	76.6e	76.3c
	Starter N+P	73.5	73.3	74.3	74.2	78.2	76.5	77.7	78.8	75.8e	
Roland 2017	No Starter	78.2	79.5	79.5	79.0	83.5	81.0	83.2	84.7	81.1a	80.3a
	Starter N+P	77.2	77.8	78.2	77.2	81.5	79.8	82.0	83.0	79.6bcd	
Winnipeg 2017	No Starter	79.3	80.2	80.0	79.0	83.7	80.8	83.7	84.2	81.4a	81.3a
	Starter N+P	78.7	79.3	79.3	79.3	83.8	81.2	83.8	83.8	81.2a	
Portage 2019	No Starter	74.5	75.2	74.7	75.0	78.7	76.5	77.8	78.7	76.4e	76.0c
	Starter N+P	74.0	74.5	73.8	74.5	78.0	75.8	76.8	78.2	75.7e	
Oakville 2019	No Starter	77.2	77.2	77.4	77.4	81.5	78.3	81.0	81.8	79cd	78.9b
	Starter N+P	76.8	76.3	78.0	76.7	81.8	78.6	80.8	82.0	78.9cd	
Winkler 2019	No Starter	78.0	78.2	78.7	77.3	81.8	78.7	80.83	81.0	79.3c	78.8b
	Starter N+P	77.3	77.2	77.2	76.8	79.2	77.3	79.48	81.5	78.2d	
All site-years	No Starter	76.1	76.9	76.9	76.2	80.2	77.9	79.8	80.4	78.1	
	Starter N+P	75.2	75.8	76.0	75.3	79.4	77.3	79.2	80.2	77.3	
Hybrid[a]		75.6E	76.5E	76.4D	75.8E	79.8B	77.6C	79.5B	80.4A		

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	<.0001
Site-year*Fert	6	0.0174
Hybrid	7	<.0001
Site-year*Hybrid	42	<.0001
Fert*Hybrid	7	0.4117
Site-year*Fert*Hybrid	6	<.0001
Coeff Var (C.V.)		4.7%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Appendix C.3. Days from planting pollen shed as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	Days after planting							
Carberry 2017	69.9yz	72.2wx	71.6xy	69.8z	74.0tuv	72.6vwx	73.8uvw	73.8tuv
Oakville 2017	74.0tuvw	74.6opqrtu	74.9prtuv	74.6qrtuv	78.1hijkln	76.7lnoqs	77.9ijkln	78.9efghijk
Roland 2017	77.7ijklno	78.7fghijklm	78.9efghijkl	78.1hijkln	82.5ab	80.4cdeg	82.6ab	83.9a
Winnipeg 2017	79.0dfghijk	79.8cdefghi	79.7cdefghi	79.2dfghij	83.8a	81.0bce	83.8a	84.0a
Portage 2019	74.3uvw	74.9pqrstuv	74.3uvw	74.8rtuv	78.4ghijklm	76.2nopqrt	77.3jklno	78.5ghijklm
Oakville 2019	77.0jklnopq	76.8klnopqr	77.7ijklno	77.1jklnopq	81.7abc	78.5ghijklm	80.9bcdef	81.9abc
Winkler 2019	77.7ijklno	77.7ijklno	78.0ijkln	77.1jklnop	80.5bcdefg	78.0ijkln	80.2cdefgh	81.3bcd

ANOVA	DF	*Pr>F*
Site-year	6	<.0001
Fert	1	<.0001
Site-year*Fert	6	0.0174
Hybrid	7	<.0001
Site-year*Hybrid	42	<.0001
Fert*Hybrid	7	0.4117
Site-year*Fert*Hybrid	6	<.0001
Coeff Var (C.V.)		4.7%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.4. Plant height at R2 growth stage as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
Carberry 2017	194s	208lmnpr	199prs	197rs	207lmnpr	199prs	211jlmnpq	210jlmnpq
Oakville 2017	230cdef	239abc	228cdefgh	234bcd	244ab	230cdefg	243ab	247a
Roland 2017	202nprs	213hijklmnpr	207lmnprs	205mnprs	216fghijlmo	203nprs	214fghijlmnp	210lmnpr
Oakville 2019	213defghijlm	220bcdefgh	215defghijl	218bcdefg	227bcdefghij	211bcdefgh	227bcdefghi	219abcde
Portage 2019	221hilmnpq	230defghijl	222fghijlmn	230efghijlmn	228cdefgjk	228ilmnpqr	228cdefgjk	232defghijlm
Winkler 2019	205mnprs	214ghijlmnp	209lmnprs	211jmnpqr	206lmnprs	206lmnprs	214ghijlmnp	202noprs

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.0061
Site-year*Fert	5	0.0131
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.4194
Site-year*Fert*Hybrid	35	0.3277
Coeff Var (C.V.)		7.3%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.5. Corn grain moisture at harvest as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
Oakville 2017	236ijklmno	254cdefgh	255cdefg	262bcde	250defghi	275b	260bcdef	262bcde
Roland 2017	214oqr	226klmnoqr	223lmnoq	222lmnoq	211qs	224lmnoq	220lmnoq	230ijklmno
Oakville 2019	226jklmnoqr	238ghijklmn	225lmnoq	227jlmnoqr	248defghik	236ghijklmno	242efghijklm	249defghi
Portage 2019	238ghijklm	265bcd	249efghij	269bcd	275bc	268bcd	280b	303a
Winkler 2019	223mnoq	217noq	221mnoq	214os	232hijklmnpq	232hijklmnpq	236ghijklmp	239fghijkl

ANOVA	DF	Pr>F
Site-year	4	<.0001
Fert	1	0.3736
Site-year*Fert	4	0.0249
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.3761
Site-year*Fert*Hybrid	28	0.8572
Coeff Var (C.V.)		10.0%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.6. Corn grain yield at harvest as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	g kg^{-1}							
Oakville 2017	10266cdefghij	11152abcde	10692abcdefgh	10713abcdefg	10301cdefghi	10747abcdefg	11552ab	11443ab
Roland 2017	7952rst	8413nopqrstu	8613klmnopqrst	8210qrstuv	7594t	8467nopqrstu	8714klmnopqrst	8456nopqrstu
Oakville 2019	10340abcdefgh	10542abcdefgh	11481ac	9788eghjklmnop	10521abcdefgh	10126befghijklm	11395acd	11037abcdf
Portage 2019	7867st	8570morstu	9236ghjklmnopqr	8461orstv	8035st	8724jklmnopqrst	9618fghjklmnpq	9724efghjklnpq
Winkler 2019	8665lnopqrstu	10086abcdefghjkm	8529pqrstuv	9160hjklmnopqrs	9797defghijklmno	10425abcdefg	10987abcdef	10620abcdefg

ANOVA	DF	Pr>F
Site-year	4	<.0001
Fert	1	0.0006
Site-year*Fert	4	0.0207
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.0334
Site-year*Fert*Hybrid	28	0.9058
Coeff Var (C.V.)		14.8%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.7. Corn test weight at harvest as affected by site-year and corn hybrid with and without in-furrow nitrogen plus phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		lb bu^{-1}									
Oakville 2017	No Starter	54.4	52.1	53.9	53.6	51.8	52.7	51.9	52.1	52.8f	52.9c
	Starter N+P	54.2	52.5	53.9	53.8	52.1	53.0	52.4	52.5	53.1efg	
Roland 2017	No Starter	55.2	52.1	54.9	54.8	52.0	53.8	52.1	53.1	53.5dfg	53.9bc
	Starter N+P	56.2	53.8	55.3	55.7	52.9	54.5	53.0	53.7	54.4bce	
Oakville 2019	No Starter	57.0	55.1	57.3	56.9	55.0	55.5	54.3	54.7	55.7ab	53.9bc
	Starter N+P	57.5	55.5	57.1	56.9	54.8	56.3	55.9	54.9	56.1a	
Portage 2019	No Starter	55.9	53.8	56.3	55.0	52.2	54.2	52.4	52.2	54cdef	55.9a
	Starter N+P	56.3	54.2	55.5	55.6	51.8	52.9	52.3	52.0	53.8cdef	
Winkler 2019	No Starter	56.2	53.8	55.3	56.7	54.4	55.3	53.2	52.8	54.7abcd	54.8ab
	Starter N+P	55.3	54.0	56.1	55.6	54.9	55.6	54.1	53.6	54.9abcd	
All site-years	No Starter	55.7	53.4	55.5	55.4	53.1	54.3	52.8	53.0	54.2	
	Starter N+P	55.9	54.0	55.6	55.5	53.3	54.5	53.5	53.3	54.5	
Hybrid[a]		55.8A	53.7C	55.6A	55.5A	53.2D	54.4B	53.2D	53.1D		

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0023
Site-year*Fert	4	0.0145
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.1566
Site-year*Fert*Hybrid	28	0.0669
Coeff Var (C.V.)		3.4%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Appendix C.8. Corn test weight at harvest as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter nitrogen plus phosphorus.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	lb bu^{-1}							
Oakville 2017	54.3 defghijklmnoqr	52.3 tuwyz	53.9 hijklmnopqrsv	53.7 jklmnopqrsv	52.0 wz	52.9 ptuvwxy	52.2 uwyz	52.3 tuwyz
Roland 2017	55.7 abcdeghi	53.0 opqrtuvwx	55.1 cdefghijkln	55.3 cdefghijkl	52.5 quvwy	54.2 fjklmnoprst	52.6 quvwy	53.4 mopqrstuvw
Oakville 2019	57.3 abcdef	55.3 gknopqstu	57.2 abcdef	56.9 abc	54.9 defghijkln	55.9 cdefg	55.1 defghijklm	54.8 defghijklmnop
Portage 2019	56.1 a	54.0 defghijklm	55.957.2 ab	55.3 bcdefhijm	52.0 vz	53.6 knopqrstuw	52.4 rvwy	52. 1vz
Winkler 2019	55.8 abcdefgh	53.9 lmnopqrstv	55.7 abcdefgh	56.2 abcd	54.7 efghijklmnop	55.5 abcdefghjk	53.7 lmnopqrstuvw	53.2 nqrtuvwx

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0023
Site-year*Fert	4	0.0145
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.1566
Site-year*Fert*Hybrid	28	0.0669
Coeff Var (C.V.)		3.40%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.9. Days from planting to silking as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	Days after planting							
Kane 2018	71.2mnopq	73.7hijklmno	72.7jklmnopq	73.2ijklmnop	75.5defghi	74.2hijkl	75.2fghijk	76.2defgh
Oakville 2018	73.3hijklmnop	74.0hijklm	73.2ijklmnop	73.8hijklmn	74.2hijkl	74.2hijkl	74.2hijkl	75.2fghijk
Portage 2018	70.8opq	70.0q	69.8q	71.3lmnopq	71.0nopq	70.7pq	71.0nopq	72.5klmnopq
Oakville 2019	77.5cdefg	77.3defg	77.7cdefg	77.2defg	81.2ab	78.2cde	81.2ab	82.5a
Portage 2019	75.2ghijk	75.5efghij	75.2ghijk	75.3efghijk	78.0cdef	76.0defghi	77.5cdefg	78.3bcd
Winkler 2019	78.2bcde	77.8cdefg	77.8cdefg	77.8cdefg	80.3abc	78.2bcde	80.3abc	81.7a

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.035
Site-year*Fert	5	0.0043
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.1846
Site-year*Fert*Hybrid	35	0.5319
Coeff Var (C.V.)		4.2%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \le 0.05$).

Appendix C.10. Days from planting to pollen shed as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean[a]	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		Days after planting									
Kane 2018	Starter N	72.0	73.3	73.7	73.0	75.7	74.8	75.8	77.5	74.5cde	73.7c
	Starter N+P	70.7	72.0	71.8	72.0	75.7	73.3	75.0	76.3	73.4fg	
Oakville 2018	Starter N	73.3	74.0	73.2	74.3	73.8	73.8	74.3	74.7	73.9ef	74.0c
	Starter N+P	73.3	74.2	73.0	73.8	74.5	74.0	75.2	75.5	74.2def	
Portage 2018	Starter N	71.5	71.5	72.0	71.3	72.3	71.7	72.8	72.8	72.0g	71.0d
	Starter N+P	72.0	70.8	70.0	72.0	72.7	72.5	72.2	73.7	72.0g	
Oakville 2019	Starter N	76.6	77.5	76.8	76.8	81.0	77.8	80.7	82.5	78.7ab	78.7a
	Starter N+P	76.9	76.3	78.0	76.7	81.9	78.6	80.9	82.0	78.9ab	
Portage 2019	Starter N	74.7	74.5	74.8	74.7	78.0	75.8	77.3	78.2	76.0c	76.4b
	Starter N+P	74.0	74.5	73.8	74.5	78.0	75.8	76.8	78.2	75.7cd	
Winkler 2019	Starter N	78.5	77.8	78.3	77.8	80.7	78.8	80.5	81.7	79.3a	78.7a
	Starter N+P	77.3	77.2	77.2	76.8	79.2	77.3	79.5	81.5	78.3b	
All site-years	Starter N	74.4	74.8	74.8	74.7	76.9	75.5	76.9	77.9	75.7	
	Starter N+P	74.0	74.2	74.0	74.3	77.0	75.3	76.6	77.9	75.4	
Hybrid[a]		73.3D	74.3D	74.2D	74.5CD	76.5B	75.2C	76.5B	77.8A		

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.0052
Site-year*Fert	5	0.0022
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.2591
Site-year*Fert*Hybrid	35	0.5088
Coeff Var (C.V.)		4.4%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Appendix C.11. Days from planting to pollen shed as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	Days after planting							
Kane 2018	71.4 txy	72.7 rstuvx	72.8 qrstuvx	72.5 qqrstuvx	75.7 hijklmnop	74.1 mopqrsuvw	75.4 hijklmnop	76.9 ghijkln
Oakville 2018	73.3 opqrstuv	74.1 lmnopqrstuv	73.1 pqrstuv	74.1 nopqrstuvw	74.2 klmnopqrstu	73.9 jklmnopqrst	74.8 lmnopqrstuv	75.1 hijklmnopqr
Portage 2018	71.8 uvwx	71.2 x	71.0 x	71.7 stuvx	72.5 vxy	72.1 uvxy	72.5 defghi	73.3 pqrstuv
Oakville 2019	76.8 fghijklmn	76.9 fghijk	77.4 fghij	76.8 fghijklm	81.5 abc	78.2 defghi	80.8 abcde	82.3 a
Portage 2019	74.4 ijklmnopq	74.5 ijklmnopqr	74.3 ijklmnopqr	74.6 ijklmnopqr	78.0 cdefgh	75.8 hijklmno	77.1 defghi	78.2 bcdefg
Winkler 2019	77.9 cdefghi	77.5 cdefghi	77.8 efhijk	77.3 cdefghi	80.0 abcdf	78.1 cdefghi	80.0 abcdf	81.6 ab

ANOVA	DF	*Pr>F*
Site-year	5	<.0001
Fert	1	0.0052
Site-year*Fert	5	0.0022
Hybrid	7	<.0001
Site-year*Hybrid	35	<.0001
Fert*Hybrid	7	0.2591
Site-year*Fert*Hybrid	35	0.5088
Coeff Var (C.V.)		4.4%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.12. Plant height at R2 growth stage as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	cm							
Oakville 2018	200jklmnop	214efghi	199klmnop	206hijklmn	218bcdefgh	197lmnop	216cdefghi	209ghijk
Portage 2018	191op	195lmnop	189p	193nop	195mnop	190op	198klmnop	195lmnop
Oakville 2019	219abcdefgh	228abc	229abc	232a	228abc	228abc	228abcde	231ab
Portage 2019	209hijkl	222abcdefg	215cdefghi	216cdefghi	227abcdef	211ghijk	225abcdef	217bcdefgh
Winkler 2019	203ijklmno	214defghi	210ghijk	210ghijk	214efghij	207hijklm	214fghi	205hijklmn

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.3385
Site-year*Fert	4	0.2852
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.215
Site-year*Fert*Hybrid	28	0.0667
Coeff Var (C.V.)		7.0%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.13. Corn grain moisture at harvest as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year[a]	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	g kg^{-1}							
Oakville 2018	262fghijklmno	304ab	261fghiklmnop	292abcde	284abcdefg	284abcdefg	275cdefghi	299abcd
Portage 2018	279abcdefghi	281abcdefgh	270abcdefghiklm	290abcdf	269abcdefghiklm	258eghiklmnop	277abcdefghi	275abcdefghi
Oakville 2019	225opq	236lmnopq	225pq	225pq	246hiklmnopq	236klmnopq	241hiklmnopq	250ghiklmnopq
Portage 2019	239mopqr	272bdefghijkl	250ghiklmnopq	267defghikln	273bdefghijk	264defghiklmn	272bdefghijkl	302ac
Winkler 2019	224pq	21.8q	224pq	214q	231nopqr	227opq	239iklmnopq	232nopqr

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0364
Site-year*Fert	4	0.7907
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.0268
Site-year*Fert*Hybrid	28	0.0385
Coeff Var (C.V.)		12.4%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.14. Corn grain moisture at harvest as effected by corn hybrid with and without in-furrow phosphorus at Portage 2018, the only site-year with a fert*hybrid interaction according to the global analysis of variance (Table 2.22).

Site-year	Fertilizer	Hybrid								Mean
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB	
		g kg^{-1}								
Portage 2018[a]	Starter N	275abc	307a	271abc	277abc	264abcd	251bcd	266abcd	253cd	271
	Starter N+P	282abc	255bcd	268abc	304ab	274abc	265abcd	289abc	298ab	279

[a] Within the column for site-year, least square mean values followed by the same letter are not significantly different (P≤0.05).

Appendix C.15. Corn grain yield at harvest as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	kg ha^{-1}[a]							
Oakville 2018	8150ijk	10020bcdef	9192efghijk	9678bcdefgh	9127efghijk	9373cdefghij	10116bcdef	9227defgijk
Portage 2018	6230mn	6205n	6525lmn	6441mn	6469mn	6032n	6370mn	6243n
Oakville 2019	10594abcde	10725abcd	11726a	9944bcdefg	10711abcde	9811bcdefgh	11732a	10932a
Portage 2019	7870klm	8661fghijk	9324defghij	8449ghijk	8038jkl	8701fghijk	9634bcdefghi	9699bcdefgh
Winkler 2019	8623fghijk	9931bcdefg	8350hijk	9367defghijk	9814bcdefg	10518abcde	10844abc	10771abc

ANOVA	DF	*Pr>F*
Site-year	4	<.0001
Fert	1	0.0308
Site-year*Fert	4	0.0025
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.0028
Site-year*Fert*Hybrid	28	0.9723
Coeff Var (C.V.)		19.7%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).

Appendix C.16. Corn test weight at harvest as affected by site-year and corn hybrid with and without in-furrow phosphorus.

Site-year	Fertilizer	Hybrid								Fertilizer Treatment Mean	Site Mean[a]
		DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB		
		lbs bu^{-1}									
Oakville 2018	Starter N	56.4	55.6	56.0	55.9	54.5	55.4	54.5	54.9	55.4	55.6a
	Starter N+P	56.7	55.8	56.5	56.4	55.1	55.8	54.9	54.9	55.8	
Portage 2018	Starter N	55.1	55.3	54.7	54.8	54.4	54.5	54.6	54.3	54.7	54.4b
	Starter N+P	54.6	54.3	55.0	54.2	54.6	55.0	54.5	54.3	54.6	
Oakville 2019	Starter N	56.7	53.6	56.1	55.2	52.9	55.0	52.5	51.8	54.2	54.0b
	Starter N+P	56.2	54.2	55.5	55.6	51.8	52.9	52.2	52.0	53.8	
Portage 2019	Starter N	56.6	55.3	56.8	56.7	54.5	55.4	54.5	54.6	55.6	55.8a
	Starter N+P	57.5	55.5	57.1	56.9	54.8	56.3	55.9	54.9	56.1	
Winkler 2019	Starter N	56.2	54.8	55.0	55.0	54.5	55.1	54.3	53.4	54.8	54.9ab
	Starter N+P	55.3	54.0	56.0	55.6	54.9	55.6	54.1	53.6	54.9	
All site-years	Starter N	56.2	54.9	55.7	55.5	54.2	55.1	54.1	53.8	54.9	
	Starter N+P	56.1	54.8	56.0	55.7	54.2	55.1	54.3	53.9	55.0	
Hybrid[a]		56.0A	54.8B	55.9A	55.6A	54.1C	55.0B	54.1C	53.8C		

ANOVA	DF	*Pr>F*
Site-year	4	0.0002
Fert	1	0.4980
Site-year*Fert	4	0.1435
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.8453
Site-year*Fert*Hybrid	28	0.2020
Coeff Var (C.V.)		2.8%

[a] Least square mean values followed by the same lower case letter (within a column) are not significantly different ($P \leq 0.05$). Least square mean values followed by the same upper case letter (within a row) are not significantly different ($P \leq 0.05$).

Appendix C.17. Corn test weight at harvest as affected by the interaction between site-year and corn hybrid in the experiment to evaluate starter phosphorus alone.

Site-year	Hybrid							
	DKC23-17RIB	DKC26-28RIB	DKC26-40RIB	DKC27-55RIB	DKC30-07RIB	DKC30-19RIB	DKC32-12RIB	DKC33-78RIB
	lbs bu^{-1}							
Oakville 2018	56.6abd	55.7abcdefghij	56.2abcdeg	56.2abcdegh	54.9efghijl	55.6abcdefghij	54.7fijkln	54.9cefghijlm
Portage 2018	54.4defghijlmop	54.4efghijlo	54.8defghijlm	54.4efghijlop	54.2ghijlnop	54.4efghijlop	54.2ghijlnop	54.2hijklop
Oakville 2019	56.3abcdef	53.9jnopq	55.8abcdefgh	55.4abcdefghil	52.3pr	53.9ijlnop	52.4opr	51.9r
Portage 2019	57.0a	55.4bcdefghijl	56.9a	56.8abc	54.7defghijlm	55.8abcdefghij	55.2defghijlm	54.7defghijlm
Winkler 2019	55.8abcdefgijk	54.4efghijlo	55.5abcdefghij	55.3abcdefghij	54.7defghijlm	55.3abcdefghij	54.2hlnop	53.5lopqr

ANOVA	DF	*Pr>F*
Site-year	4	0.0002
Fert	1	0.4980
Site-year*Fert	4	0.1435
Hybrid	7	<.0001
Site-year*Hybrid	28	<.0001
Fert*Hybrid	7	0.8453
Site-year*Fert*Hybrid	28	0.2020
Coeff Var (C.V.)		2.8%

[a] For all means within the entire table, means followed the same lower case letter are not significantly different ($P \leq 0.05$).