NUTRIENT UPTAKE AND NITROGEN FIXATION BY FABA BEAN IN SASKATCHEWAN SOILS

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Abstract

As faba bean (*Vicia faba* L.) production expands in western Canada, limited information is available for modern faba bean cultivars relating to their nutrient requirements and removals, biological nitrogen fixation (BNF), and responses to fertilization. This information is needed to properly manage fertility in cropping rotations containing faba bean. To address this knowledge gap, field studies were conducted at four sites located in the Dark Grey, Black and Dark Brown soil-climatic zones in south-central Saskatchewan in 2016 and 2017. Using four modern zero tannin faba bean cultivars, the effects of two fertilizer treatments on faba bean straw and grain yield, macronutrient (N, P, K, S, Ca, Mg) and micronutrient (Cu, Zn, Fe) concentration and uptake were examined. In addition, a glasshouse experiment was conducted with three P fertilizer rates added to a P deficient soil and two cultivars of faba bean grown, with the above- and belowground yield, N and P concentration and uptake and nitrogen derived from atmosphere (%Ndfa) measured. Soil available nutrients were also measured pre-seeding and post-harvest. The faba bean cultivars demonstrated high yield potential in most site-years, with no significant effect of fertilization or cultivar on yield (~4-6 tonnes ha^{-1}), and average grain N uptake (117-300 kg N ha^{-1}) and grain P uptake (34-82 kg P_2O_5 ha^{-1}) were generally dependent on soil and environmental conditions experienced according to site location. The N and P uptakes were generally higher compared to uptakes by faba bean and other pulses reported in previous Saskatchewan field studies. Nitrogen accumulated from biological nitrogen fixation (BNF) was about 88 %Ndfa by faba bean, as estimated in the glasshouse study. Given ~230 kg N ha^{-1} found in aboveground biomass (grain+straw) in the field studies, an estimated ~ 200 kg N ha^{-1} was potentially contributed from BNF by faba bean. Overall, the high removal of nutrients in faba bean grain observed in this research suggests that fertility management in rotations with faba bean should pay attention to drawdown in the soil over the long-term when faba beans are frequently included in rotation and the grain is harvested.

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DEDICATION

I lovingly dedicate this thesis to my parents, Tammy and Gerald Klippenstein, who continue to support myself and my brothers throughout our countless combined years of education, our numerous moves throughout western Canada (and beyond) and our ongoing life choices. Though we haven't always lived nearby, your love and dedication to your family goes far beyond the distance we have travelled from "the nest". You instilled in us the notion that it takes a village to raise a child and you have given us the means to grow within and cherish each new community we find ourselves in, even as adults. Thank you for not only providing the opportunities we have had in our lives, but also for providing the love and support needed to help us find our own versions of success.

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AA	Atomic absorption
AICc	Corrected Akaike's Information Criterion
ANOVA	Analysis of variance
BNF	Biological nitrogen fixation
CRD	Complete randomized design
DTPA	Diethylene-triamine-penta acetic acid
EC	Electrical conductivity
FE	Flame emission
HI	Harvest index
IHARF	Indian Head Agricultural Research Foundation
K_2SO_4	Potassium sulfate
MAP	Monoammonium phosphate
MK	Modified Kelowna
N_2	Atmospheric nitrogen
Ndfa	Nitrogen derived from atmosphere
Ndff	Nitrogen derived from fertilizer
Ndfs	Nitrogen derived from soil
NHI	Nitrogen harvest index
NH_4^+	Ammonium
NO_3^-	Nitrate
PHI	Phosphorus harvest index
PPD	Pulse planting density
RCBD	Randomized complete block design
SO_4^{2-}	Sulfate
SPG	Saskatchewan Pulse Growers
%Ndfa	Percentage of nitrogen derived from atmosphere
%Ndff	Percentage of nitrogen derived from fertilizer
%Ndfs	Percentage of nitrogen derived from soil

1. General Introduction

1.1 Introduction

Interest in growing faba bean (*Vicia faba* L.) and acres of faba bean production in Saskatchewan have increased, influenced by the introduction of new cultivars with increased yield potential and biological nitrogen fixation (BNF) and the ability to resist diseases that negatively affect other pulses grown in the region such as root rot caused by *Aphanomyces euteiches* in field pea and lentil. Faba bean is used as both an annual crop in conventional rotations and as a green manure crop in organic rotations in Saskatchewan but there is little to no information on nutrient requirements of faba bean cultivars grown under Saskatchewan conditions. As the desire for minimizing the environmental footprint of agriculture grows, efficient use of fertilizers and maximizing the contribution of BNF are becoming more important, and more grain legume (pulse) crops like faba bean are being included in cropping system rotations. Not only must nutrient requirements be met for a target faba bean crop yield, but nutrients removed by faba bean need to be accounted for to make proper fertilizer recommendations and maintain fertility for crops in successive cropping years. There is a need for grain and straw yield fertilization response studies and information on the amount of macronutrients taken up and removed by faba bean crops on the prairies. Micronutrient uptake and removal information is also needed in Saskatchewan, both for crop production and for marketability for human and animal consumption.

To address these identified gaps, field studies were conducted in 2016 and 2017 and a glasshouse study was conducted in 2017. The study results are intended to contribute to improved crop nutrition planning by Saskatchewan growers who intend to include faba bean crops in their rotation. Four zero tannin faba bean cultivars were grown in a two-year field study at four locations in Saskatchewan. The effect of different environmental conditions and soil type were considered by having four different field sites in each of two years (2016 and 2017) in different soil-climatic zones and in conditions where faba beans are normally grown in Saskatchewan. Two different fertilizer treatments, 1) unfertilized, and 2) fertilized with nitrogen (N), phosphorus (P), potassium (K) and sulfur (S), were used. Assessment of grain and straw biomass and nutrient concentration was used to determine yield, uptake and removal of soil macro- and micronutrients. Soil available nutrients were also assessed pre-seeding and post-harvest.

The glasshouse component of the thesis research was conducted to address the limited information in western Canada on how P fertilization of faba bean influences faba bean growth and the proportion of nitrogen derived from atmosphere (%Ndfa) through BNF. This study aimed to determine the effect of applied P fertilizer on the yield and BNF of two cultivars of faba bean, using ^{15}N-labelled urea and the ^{15}N isotope dilution method under the relatively controlled conditions of a glasshouse. Measurements made in the glasshouse study were yield, N and P content and uptake by above- and belowground plant material, and %Ndfa and amount of nitrogen derived from atmosphere (Ndfa) by aboveground plant material, of two different faba bean cultivars.

The following hypotheses are addressed in this thesis research:

a. Faba bean yield and nutrient uptake in the field will differ with growing environment, fertilization, and cultivar. Faba bean nutrient uptake will be higher than other pulse crops grown on the prairies. Partitioning of nutrients between straw and grain will favour the grain component in faba bean, similar to other pulse crops.
b. Faba bean yield and BNF will respond positively to P fertilization of a P deficient soil.
c. Faba bean will have greater requirements for macro- and micronutrients, higher N yield (aboveground N content) and greater BNF, than other pulse crops in recent studies.

To address these hypotheses and provide new information on yield, uptake and removal of soil macro- and micronutrients, BNF and P fertilizer response by faba bean cultivars grown in Saskatchewan, the following objectives for this thesis were established:

a. To determine faba bean yield, concentration and uptake of macronutrients: N, P, K, S, calcium (Ca), magnesium (Mg), and micronutrients: zinc (Zn), copper (Cu), and iron (Fe) in grain and straw, with and without added fertilizer. Eight field trials were conducted over two years (2016 and 2017) at four Saskatchewan sites to address this objective.
b. To evaluate BNF, faba bean yield response (aboveground and belowground biomass yield) and N and P content of two faba bean cultivars as influenced by P fertilization. A glasshouse experiment was conducted in 2017 to address this objective.

c. To compare uptake and crop removal of macro- and micronutrients by faba bean to other pulse crops, including soybean, lentil and pea, using data from recent studies.

1.2 Structure of Thesis

This thesis is comprised of two separate main chapters containing the research intended for publication. Chapter 1 precedes the main research chapters and contains a general introduction of the thesis, justification for the research and the hypotheses and objectives of the thesis research work. Chapter 2 follows the introduction and is a review of relevant literature that covers the production and benefits of faba bean, nutrient requirements and partitioning in faba bean, BNF by faba bean and the genetic, environmental and management influences on faba bean yield and nutrition. The first main research chapter, Chapter 3, focuses on factors influencing N and P in faba bean and describes the results of the field studies and the glasshouse study. Chapter 4 covers the results of the field studies for K, S, Ca, Mg and micronutrients (Zn, Cu, Fe). A synthesis and conclusion of the findings from the main research chapters is contained in Chapter 5, and Chapter 6 is a compilation of the literature cited in this thesis. Additional information from the field studies and the glasshouse study, along with ANOVA tables are provided in the appendix.

2. Literature Review

2.1 Production and Benefits of Faba Bean

2.1.1 Production of faba bean

Faba bean (*Vicia faba* L.) is a pulse crop grown in many countries for use as a protein source for animal feed, human consumption (Köpke and Nemecek, 2010; Jensen et al., 2010; Pötzsch et al., 2018) and in industrial products (Siddique et al., 2012; Hossain et al., 2018). Considerable research relevant to faba bean production has been conducted in regions including Australia, Europe, the Mediterranean zone, and Canada, providing important information on faba bean agronomy in contrasting soil and environmental conditions.

Though commercial faba bean crops have been grown in western Canada since 1972 (Graf and Rowland, 1987), seeded acres remained low in the first decades since introduction, largely due to limited market access and low commodity prices (Slinkard and Buchan, 1980; Graf and Rowland, 1987). More recently, faba bean area seeded in Canada has generally increased due to the availability of modern faba bean cultivars that have greater genetic yield potential and more resilience to stress, along with the expansion of markets for the crop. Land area seeded to faba bean in Canada over the five-year period 2014-2018 is shown in Fig. 2.1. The area seeded to faba bean in Saskatchewan has grown more rapidly, increasing from about 7,700 ha in 2014 (Fleury and Barker, 2016) to 24,300 ha in 2017 (Government of Saskatchewan, 2017).

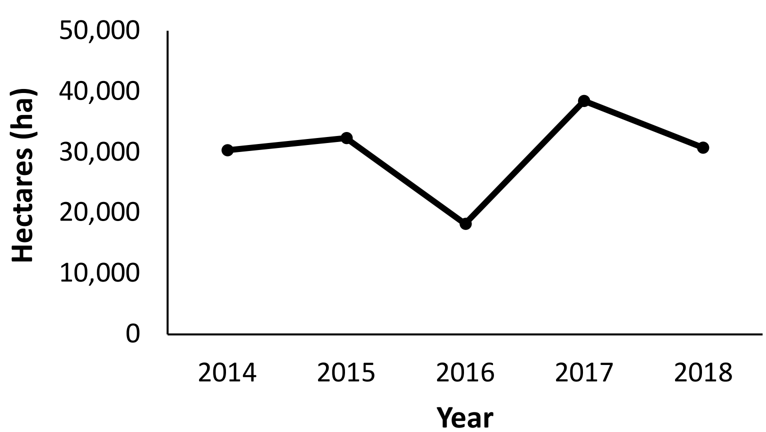

Fig. 2.1. Faba bean seeded area (ha) in Canada in the past 5 years (Statistics Canada, 2018).

2.1.2 Benefits of faba bean

A desire by growers to realize the rotational benefits of having a pulse crop in rotation, especially the biological nitrogen fixation (BNF) component, has likely contributed to increased seeded area of pulses over the last several years in western Canada. Along with other pulse crops, faba bean as a legume is considered ecologically and agronomically beneficial to include in cropping rotations. The benefits gained from inclusion of faba bean in a cropping rotation are largely due, but not limited, to the ability of faba bean to fix atmospheric nitrogen (N_2) for use by the faba bean crop itself and to contribute to the nitrogen (N) soil pool (Walley et al., 2007) to supply N for following crops. Another benefit is the greater resistance that faba bean has shown to root rot diseases such as *Aphanomyces eueiches*, compared to other more susceptible pulse crops like peas and lentils. Faba bean is commonly used as a green manure crop, particularly in organic cropping systems, and can contribute to greater yields in following crops (Wani et al., 1994) and greater long-term improvements in cropping systems (Wani et al., 1991; Jensen et al., 2010). The contributed amount of N when the grain is harvested and removed from the field is smaller than if the grain is not harvested and the crop is turned under as green manure, because much of the N in faba bean is removed with the grain (Wright, 1990a; Stevenson and van Kessel, 1996). Even though lesser amounts of N are contributed to following crops when pulse grains are harvested, barley and wheat yields typically increase when grown after faba bean in rotation (Bailey, 1986; Wright, 1990b; Amanuel et al., 2000; Cazzato et al., 2012). Wheat yield has also been reported to increase the second year after faba bean is grown, though the increase is lower than in the first year following faba bean (Armstrong, 1986; Wright, 1990b). These yield increases are mainly due to the additional non-N related benefits that pulse stubble provides for cereal crops, rather than a large direct N benefit (Wright, 1990a; Strydhorst et al., 2008). A benefit that is related to timing of available N supply from residue such as faba bean is increased seed protein concentrations in wheat (Strydhorst et al., 2008) and barley (Wright, 1990a) grown in the following year. Increased seed protein concentrations of following cereal crops may be attributed to a later season supply of available N.

Non-N related benefits are affected by various biotic and abiotic factors. They are also dependent on the different species of pulses grown, relative impacts on break in pest cycles, and how pulse stubble interacts with the soil to affect chemical, biological and physical conditions, and the following crop in rotation, differently than cereal residue does. Examples of non-N related benefits include improved soil biological activity (Mona et al., 2011; Cazzato et al., 2012), and reduction of soil-borne pathogens (Bainard et al., 2017; Hossain et al., 2018).

Overall, faba bean crops can make a positive contribution to the N economy in a soil-plant system (Walley et al., 2007), and less added N fertilizer is needed to maximize yields of cereal crops grown on faba bean residue (Jensen et al., 2010; Adak and Kibritci, 2016) compared to those grown on cereal residue. However, it is still difficult to formulate a fertilizer recommendation for a crop grown after faba bean based on crop yield or N uptake due to biotic and abiotic factors that cause variations in N mineralization rate, and therefore in N contribution to the following crop (Walley et al., 2007). A need was identified early on for information on the response of modern faba bean cultivars to fertilization (Henry et al., 1995), and this need remains as faba bean acres increase in Saskatchewan. Various studies have assessed the yield, N uptake and partitioning in faba bean, but there is limited current information on faba bean requirements for other macro- and micronutrients.

2.1.3 Limitations of faba bean

Although there are many benefits of including faba bean in a cropping system, there are also limitations regarding faba bean production. First, there is limited information on faba bean production compared with production of other pulses, particularly dryland faba bean production, as evident in an international pulse based meta-analysis conducted by Walley et al. (2007) and an international literature survey conducted by Anglade et al. (2015). Second, faba bean yield and growth are variable and can be limited by insufficient moisture, as discovered in a study in south-western Australia (Mwanamwenge et al., 1998) and a study in Iran (Ghassemi-Golezani et al., 2009). This restricts faba bean production in more arid soil climatic-zones, such as the brown, semi-arid soil climatic-zone in southern Saskatchewan. The need for specialized equipment due to difficulty in seeding large, irregularly shaped faba bean cultivars and limited markets within Canada are other factors, though they are not commonly addressed in literature.

2.2 Yield, Nitrogen Requirements and Partitioning in Faba Bean

2.2.1 Faba bean yield

Faba bean aboveground grain and straw yields, the associated nutrient content and their relationship to other crops, will vary from year to year and location to location, as a result of different soil-climatic conditions each growing season. A field study conducted by Hossain et al.

(2017) in Swift Current, Saskatchewan reported that faba bean seed yield was highly variable over three consecutive growing seasons: 2008, 2009 and 2010. When faba bean was compared to chickpea, dry bean, field pea and lentil, the seed yield of faba bean (886 kg ha^{-1}) and dry bean (870 kg ha^{-1}) at Swift Current were significantly lower than chickpea (2227 kg ha^{-1}), field pea (2244 kg ha^{-1}) and lentil (1904 kg ha^{-1}), in the year where there was less moisture (2008). Swift Current is located in the semi-arid soil climatic zone and is typically dry but receives variable amounts of precipitation from year to year. In years with higher moisture (2009 and 2010), the seed yield of faba bean and field pea were significantly higher than other pulses. Faba bean seed yield was 1,948 kg ha^{-1} in 2009 and 3,009 kg ha^{-1} in 2010, and field pea seed yield was 2,039 kg ha^{-1} in 2009 and 2,972 kg ha^{-1} in 2010. This indicates that faba bean responded positively to wetter conditions. Faba bean straw yield (2,015 kg ha^{-1}) was less variable, but also showed a similar trend of being significantly lower than other pulses in the dry year of 2008 along with dry bean (1,740 kg ha^{-1}), and increased in the wetter years with a significantly higher straw yield of 2,032 kg ha^{-1} in 2009 and 4,634 kg ha^{-1} in 2010 (Hossain et al., 2017). In a study conducted at sites having typically more moist conditions, including the Dark Brown (Saskatoon, Saskatchewan) and Black (Rosthern, Saskatchewan) soil climatic zones, Bueckert et al. (unpublished, 2011) observed faba bean total biomass (grain and straw) yield ranging from 8,500-16,700 kg ha^{-1}, with seed yields of 4,470-6,500 kg ha^{-1} in 2009, a cool year with late season rains.

2.2.2 Nitrogen requirements and partitioning in faba bean

In years and locations where environmental conditions result in faba bean producing higher biomass and yields, larger amounts of nutrients are taken up and removed in grain harvest compared to other pulses. For example, Hossain et al. (2018) at Swift Current found that across all three growing seasons the average seed N uptake of faba bean (79 kg N ha^{-1}) was second only to field pea (81 kg N ha^{-1}) and that the average straw N uptake of faba bean (47 N kg ha^{-1}) was the highest, followed by chickpea and lentil. At sites near Saskatoon and Rosthern, Bueckert et al. (unpublished) found that faba bean total shoot N was 320-470 kg N ha^{-1} and that a large amount of N (200-350 kg N ha^{-1}) was removed in the high (30%) protein seed. In early work with old cultivars, Richards (1977) found that faba bean with a yield of only about 2,000 kg ha^{-1} contained a lower amount of total plant N (194 kg ha^{-1}), compared to more recent studies with higher yielding cultivars, but they also reported seed produced with ~ 30% protein content.

Three different Australian studies also reported high total N concentration and uptake by faba bean (Rose et al., 2016) and high straw N uptake (Jensen et al., 2010; Peoples et al., 2009) compared to other pulse crops. The proportion of the N contained in mature faba bean grain that is removed in harvest, and the extent to which the faba bean N may be obtained through BNF versus the soil, is important when considering the impact of faba bean on the soil N balance.

The partitioning of N in plants among different plant parts is important because it affects the amounts of N that are removed from the system when different plant parts are harvested. The accumulation of N in faba bean leaves, stems and pods is the highest at the beginning of seed-filling and can decrease by about 50% by the end of seed-filling as N is moved from these plant parts into the seed (Herdina and Silsbury, 1990). Due to the high protein content of faba bean seed, a large amount of N is exported in the seed (Beck et al., 1991; Walley et al., 2007), and a rather constant N concentration is maintained in the seed even as it increases in weight (Herdina and Silsbury, 1990). As such, there is a high N requirement during seed-filling while at the same time N accumulation from BNF and soil is decreasing. Nitrogen from BNF and soil N sources often cannot meet the faba bean seed N requirements, so N is remobilized from the stalk, leaves and pods into the seed (Salon et al., 2001; Schiltz et al., 2005; Hossain et al., 2018), leaving less N fixed in faba bean straw biomass than contained and removed in the seed (Beck et al., 1991; Walley et al., 2007). Although varying amounts of N accumulated in faba bean seed have been reported in different studies, most studies report that at least 50% of total plant N is found in the seed by maturity, and typically proportions in the seed are higher. For example, Dayoub et al. (2017) and Herdina and Silsbury (1990) reported that faba bean seed held over 50% and 78% of plant N by maturity, respectively, and Bueckert et al. (2011) reported that faba bean seed contained 2/3 of the total plant N. Hossain et al. (2018) attributed the higher seed N uptake by faba bean to greater seed yield and greater ability to fix N_2 compared to the other pulses in the study.

The N content of pulse roots is not usually estimated or measured in most N balance studies. Therefore, there is a need to further study the effect of added fertilizer and soil macronutrients on faba bean root systems, along with their effect on faba bean yield, macro- and micronutrient concentration, uptake and BNF. A few studies on the Canadian prairies, summarized in Table 2.1, have provided estimated N uptake values for all parts of the faba bean plant, including belowground plant parts. Based on a study in Manitoba, Richards (1977) estimated that 20% of total faba bean N was contained in roots, with 60% in seed and 20% in leaves, stems and pods. The estimates for belowground N in the study conducted by Bueckert et al. (2011) at two Saskatchewan site locations were based on the ratio used by Ross et al. (2008), where total aboveground biomass accounted for 2/3 of all plant N, and belowground biomass accounted for 1/3 of all plant N. Estimated faba bean above- and belowground N values reported by both Ross et al. (2008) and Dyck et al. (2012) were an average of total plant N estimates for western Canada from a long-term study (estimates from 1982-2005) conducted at the Hendrigan plots in Breton, Alberta. Bueckert et al. (2011) found that after the seed was removed, 100-150 kg N ha^{-1} was left in aboveground biomass (stalks, stems, pods, senesced leaves) to contribute to succeeding crops. When the N contribution of belowground biomass was accounted for in the total N contribution it was assumed that a total of 150-270 kg N ha^{-1} of above- and belowground biomass would contribute to the succeeding crop in readily and slowly available forms of N (Bueckert et al., unpublished). Gaseous, leaching and runoff losses of 30% per year by legume residues (Ross et al., 2008) were considered in the calculation.

Table 2.1. Partitioning of estimated nitrogen (N) uptake in faba bean among different plant parts reported in studies on the Canadian prairies.

Authors	Total N	Seed N	Shoot N	Belowground N
		kg N ha^{-1}		
Richards, 1977	194	116 (60%)	39 (20%)	39 (20%)
		---------*Aboveground N*---------		
Bueckert et al., 2011†	480-710	320-470 (66%)		160-240 (34%)
Dyck et al., 2012‡	50.5	33.3 (66%)		17.2 (34%)

† Aboveground faba bean N values were measured, and belowground N values were based on belowground N estimations (34%) by Ross et al., 2008.
‡ Above- and belowground estimates based on data from a long-term study (estimates from 1982-2005) conducted at the Hendrigan plots in Breton, Alberta.

Although the value of N contribution for each faba bean plant part is not available for most studies, belowground N was estimated at 30% of total pulse N in a review of global N_2 fixation by Herridge et al. (2008), at 1/3 of total pulse N in a study in Saskatchewan conducted by Bremer et al. (1988), and root N was estimated at 14% of total pulse N in a later study in Saskatchewan by Bremer (1991). In a glasshouse study in South Australia, Herdina and Silsbury (1990) reported that belowground N made up about 9% of average total faba bean N (12 kg N ha^{-1}). They indicated that if this percentage of belowground N was applied to a field setting, faba bean would not provide enough N to make a positive contribution of N to soil or a following crop unless the crop was grazed or incorporated back into the soil to contribute additional N from faba bean seed (68% of total N; 90 kg N ha^{-1}) or a large portion of the straw (23% of total N; 30 kg N ha^{-1}) to supplement the small contribution of root N.

2.3 Biological Nitrogen Fixation by Faba Bean

2.3.1 Biological nitrogen fixation

Apart from N, the nutrients that faba bean requires can only be obtained from soil and/or fertilizer sources. However, the N that faba bean requires can largely be obtained from atmospheric N (N_2) sources when *Rhizobium leguminosarum* is present (Richards and Soper, 1982) and actively fixing nodules are formed on the faba bean roots. Biological nitrogen fixation (BNF) is the symbiotic relationship between N_2-fixing *Rhizobium* bacteria and legume plants that allows the legume plant to form root nodules and fix N_2 into a useable form of N for the plant. Plant growth and high-protein content in pulse crops is supported by BNF (Peoples et al., 2009; Denton et al., 2017), and the reliance of pulses on inorganic soil N and N fertilizer decreases when BNF occurs (Walley et al., 2007). *Rhizobium leguminosarum* bv. *viciae* is the species responsible for BNF in faba bean root-nodules and can be present in the soil or added to the seed or soil as an inoculant when faba bean is seeded in order to ensure BNF occurs during the growing season. Though faba bean seedlings rely on N from seed reserves and mineral sources until nodules are formed and start fixing N_2, BNF provides faba bean with N throughout most of the growing season and can continue to fix N_2 in the late growth stages until the onset of plant maturity (Jensen et al., 2010; Sprent and Bradford, 1977; Richards and Soper, 1982). Based on a glasshouse study in southern Australia, Herdina and Silsbury (1990) estimated that 80% of BNF contributed directly to N in faba bean grain. As for the contribution of BNF to total aboveground faba bean N, Richards and Soper (1982) found that 63-71% of aboveground N (54-111 kg N ha^{-1}) was obtained from BNF in five out of their seven field trials in a field study in Manitoba. A lower percent of aboveground N obtained from BNF (37%) was due to poor growth at one of the sites and results showed that no aboveground N was contributed by BNF in the other site, due to excess amounts of plant-available NO_3 present (Richards and Soper, 1982).

Not only does BNF contribute to the accumulation of N in aboveground pulse plant biomass, but in a meta-analysis conducted by Walley et al. (2007) that assessed the contribution of BNF of pulses in the Northern Great Plains, reports showed that BNF by pulse crops can increase the amount of N contributed to the soil over time. Faba bean is often able to fix greater amounts of N_2 than other pulses and is therefore one of the pulses that can potentially contribute

N to a positive soil N balance in the long term. A net positive addition of N to the soil occurs when the proportion of nitrogen derived from atmosphere (%Ndfa) is greater than the nitrogen harvest index (NHI), the ratio between grain N content and total shoot N (Walley et al., 2007; Anglade et al., 2015), and therefore when the %Ndfa is greater than the percentage of N in the plant removed through harvesting the grain. Generally, more N from BNF is removed in pulse grain than remains in above- or belowground biomass (Beck et al., 1991). Because there is less N from BNF in shoot residues, roots and root exudates than in grain, N from BNF for these plant parts is overestimated if it is estimated as equal to the N from BNF in grain (Walley et al., 2007). The contribution of N from BNF can be underestimated if the amount of N from BNF in shoots is estimated as the total amount of N from BNF in the plant and the contribution of N from BNF in belowground biomass is not accounted for (Carlsson and Huss-Danell, 2003; Walley et al., 2007; Anglade et al., 2015).

2.3.2 Measuring biological nitrogen fixation

The amount of N_2 a faba bean crop fixes through BNF depends on how much the crop relies on BNF for plant growth (i.e. the proportion of the crop N derived from N_2 or %Ndfa) and the total amount of N it takes up during the growing season (Jensen et al., 2010). Although the total amount of N accumulated by faba bean is easily determined by measuring plant N concentration and yield and calculating N uptake, there are several different methods to measure %Ndfa. Two commonly used methods are the ^{15}N isotope dilution and A-value methods, though the ^{15}N isotope dilution method is preferred and more widely used for field studies that require time-integrated measurements of BNF (Unkovich and Pate, 2000). This method considers ^{15}N and ^{14}N, two naturally occurring isotopic forms of N, and compares their ratio ($^{15}N/^{14}N$) in N_2-fixing legume plants and non-fixing reference plants to estimate the %Ndfa (Danso et al., 1993; Hossain et al., 2017). Nitrogen sources include native N from the soil (Ndfs), N_2 from the atmosphere (Ndfa), and N from fertilizer labelled with ^{15}N (Ndff) (Danso et al., 1993; Rennie, 1982; Xie et al., 2017). Additional unlabelled N from the atmosphere dilutes the ^{15}N content compared to a non-legume. The more N_2 fixed into the plant, the lower the $^{15}N/^{14}N$ ratio in the legume and higher the %Ndfa. The %Ndfa is calculated from the difference in ^{15}N content of the N_2-fixing and non-fixing reference plants and is based on the assumptions that: (1) the same proportion of N from ^{15}N labelled fertilizer and inorganic soil N are taken up by the N_2-fixing and non-fixing reference plants during the total period of growth, and (2) no Ndfa from the N_2-fixing crop is taken up by the non-fixing reference crop (Chalk, 1985; Hardarson and Danso, 1993; Xie, 2017).

2.3.3 Biological nitrogen fixation by faba bean compared with other pulses

In studies examining BNF in pulses in Saskatchewan, North America and elsewhere, faba bean had higher mean, median and maximum values of %Ndfa and BNF (kg N ha^{-1}) than other pulses, as shown in Table 2.2. Other studies not included in this table also show that faba bean has a higher %Ndfa compared to other pulses (Adak and Kibritci, 2016; Hardarson et al., 1991; Hossain et al., 2017). Data in the global literature survey by Anglade et al. (2015) showed that faba bean was able to fix a greater amount of shoot N than all the other pulses, which was further supported by the survey of organic crop rotations conducted by Anglade et al. (2015) in the Paris basin, France, that estimated the amount of shoot N and total N fixed by pulses, the amount of shoot N fixed by faba bean, 127 kg N ha^{-1} yr^{-1}, was greater than field pea and lentil, which fixed 85 and 40 kg N ha^{-1} yr^{-1}, respectively. Not surprisingly, the total N estimated to be fixed by faba bean, 165 kg N ha^{-1} yr^{-1}, was also greater than field pea and lentil, which fixed 111 and 52 kg N ha^{-1} yr^{-1}, respectively.

Table 2.2. Proportion of nitrogen derived from the atmosphere (%Ndfa) and biological nitrogen fixation (BNF) of pulse crops reported for regions of Saskatchewan, North America and globally.

Authors	Region	Faba bean	Lentil	Field pea	Chickpea	Common bean
		Ndfa				
		%				
Bremer et al., 1988	Saskatchewan, Canada	71[†]	46	54	-[‡]	-
Hossain et al., 2017	Saskatchewan, Canada	67[†]	54	54	52	26
Walley et al., 2007	Northern Great Plains, North America	88[§]	~60	~55	Kabuli: <45 Desi: ~55	<45
Jensen et al., 2010	North America	88[†¶]	60	56	50	-
Peoples et al., 2009	North America	74[†¶]	-	59	54	49
Anglade et al., 2015	Global	75[§¶]	66	71	-	-
		BNF				
		kg N ha^{-1}				
Bremer et al., 1988	Saskatchewan, Canada	160[#]	75	105	-	-
Hossain et al., 2017	Saskatchewan, Canada	68[†]	49	54	52	9
Jensen et al., 2010	North America	135[†¶]	50	83	54	-
Peoples et al., 2009	North America	118[†¶]	-	83	54	75
Anglade et al., 2015	Global	139[†¶]	72	82	-	-

† All values in the row are mean values.

‡ Data not reported.

§ All values in the row are median values.

¶ All values in the row are based on shoot N.

All values in the row are maximum values at the least drought-stressed sites in the study.

It should be noted that most faba bean results reported in Peoples et al. (2009) and Jensen et al. (2010) were obtained from irrigated faba bean crops. Also, the number of studies that published %Ndfa estimates for faba bean in the meta-analysis by Walley et al. (2007) was less than 1/3 of the number of studies for the other pulse crops, and there was only one faba bean and one dry bean cultivar available for use in the experimental area in the study by Hossain et al. (2017), so data on BNF and yield potential for these two pulses are also limited. There is a need to expand and update the BNF data for faba bean in western Canada.

2.3.4 Factors affecting biological nitrogen fixation

Biological nitrogen fixation is often regulated by legume plant growth (Peoples et al., 2009), therefore the amount of N_2 fixed is essentially determined by the factors that directly affect plant growth (Anglade et al., 2015). Many different factors influence BNF, but environmental, edaphic and management factors have the greatest influence on BNF and account for high BNF variations between similar species or the same genotype of species grown near one another (Walley et al., 2001, 2007; Anglade et al., 2015).

2.3.4.1 Environmental factors

It is reported that drought stress significantly limits BNF and yield of pulse crops, especially under dryland conditions in semi-arid regions of western Canada (Hossain et al., 2017, 2018; Bremer et al., 1988). More specifically, in a study estimating the BNF in Canadian agricultural land by Yang et al. (2010), Saskatchewan had the lowest rate of BNF of all Canadian provinces due to its semi-arid conditions. Results from two different studies in the semi-arid Canadian prairies, roughly 40 years apart, show the negative influence of low moisture levels on BNF. In a study with two site locations in southern Manitoba, Dean and Clark (1977) observed that rhizobia may become parasitic to the pulse plant in moisture stressed conditions and use the limited photosynthate provided to meet nodule demand, which would limit the nutrient supply that reaches the vegetative plant parts and indirectly limit BNF. In a three-year study near Swift Current, Saskatchewan, Hossain et al. (2017, 2018) observed that pulses had more nodules and higher amounts of BNF in the study year with the highest moisture level (2010) and were negatively affected by low moisture in the other two years (2008 and 2009). Other studies have shown that BNF and grain yield are affected by environmental conditions, specifically low rainfall that limits the soil water available (Bremer et al., 1988; Peoples et al., 2009; Hossain et al., 2017). Carlsson and Huss-Danell (2003) found that the amount of dry matter and BNF in legumes are significantly correlated. Interestingly, in a study by Bremer et al. (1988), although all pulses were affected by drought stress, field pea and lentil fixed N_2 more effectively in drought-stressed conditions while faba bean fixed N_2 more effectively in higher moisture conditions.

2.3.4.2 Edaphic factors

Another common factor that interferes with BNF in pulses is plant available inorganic N in the soil, an edaphic factor most commonly present as nitrate (NO_3) (Caba et al., 1993). Soil conditions such as salinity or pH can also affect BNF, but available inorganic soil N (NO_3 and ammonium (NH_4)) is considered the most influential soil fertility factor on BNF (Van Kessel and Hartley, 2000). Available inorganic soil N greatly influences %Ndfa in pulses (Unkovich and Pate, 2000; Voisin et al., 2002; Cazzato et al., 2012), often in a negative way (Bremer et al., 1988; Buttery et al., 1992; Hossain et al., 2017). For example, Bremer et al. (1988) found that increasing soil NO_3 levels decreased %Ndfa proportionally, much like increasing drought stress levels decreased %Ndfa. Hossain et al. (2017) found a negative correlation between %Ndfa and both soil N uptake and available inorganic soil N (NO_3 and NH_4). Moreover, Van Kessel and Hartley (2000) found that regardless of how other factors influenced BNF, if the level of available inorganic N met or exceeded the pulse crop N requirements, BNF was limited.

Though pulses are generally affected by large amounts of available inorganic soil N in a negative way, each pulse species is affected differently and to varying degrees. Hossain et al. (2017) showed that the correlation between BNF and soil N uptake by faba bean was not consistent and suggested the inconsistency was because faba bean requires greater amounts of soil N than other pulses (Rose et al., 2016), though varying environmental conditions among the three years of the study could also have affected the relationship between BNF and N uptake by faba bean. The ability of faba bean to overcome the inhibitory effect of greater soil N on BNF better than other pulses was another suggestion of Hossain et al. (2017) as to why correlations between %Ndfa and soil N uptake were non-significant, which is supported by various other studies (Harper and Gibson, 1984; Chalifour and Nelson, 1987; Hardarson et al., 1991; Schwenke et al., 1998; Turpin et al., 2002; Köpke and Nemecek, 2010; Dayoub et al., 2017). For example, a study in western France by Dayoub et al. (2017) observed that soil N uptake and BNF by faba bean can occur simultaneously and at a greater level than other pulses, and nodules could still be established by faba bean when high levels of available inorganic soil N were present. These findings are similar to other studies where high levels of BNF by faba bean were still able to occur in the presence of high soil N, unlike BNF by other pulses (Harper and Gibson, 1984; Turpin et al., 2002; Köpke and Nemecek, 2010). On the other hand, when available inorganic N levels were low, Dayoub et al. (2017) found that faba bean seedlings were able to use seed N reserves to meet their N requirements for a significant period of time, as previously found by Herdina and Silsbury (1990). These findings show how faba bean is able to adapt to and effectively use different levels of available inorganic soil N and different sources of N to meet plant N requirements more effectively than other pulses under similar conditions.

2.3.4.3 Management factors

Along with being affected by many environmental and edaphic factors, certain management factors can also influence the amount of BNF obtained by pulse crops. For example, decreasing weed interference (Strydhorst et al., 2008) or increasing seeding density index (Danso et al., 1987) can increase BNF by pulses, especially faba bean. Optimal reported seeding densities for faba bean have increased over the years, from 38 plants m^{-2} determined by Graf and Rowland (1987) in Saskatchewan to 68-90 plants m^{-2} in a study by Strydhorst et al. (2008) in Alberta. The main reason for increased seeding density recommendations in recent years is to decrease weed biomass and allow for greater pulse seed and BNF yields that occur as a result. Strydhorst et al. (2008) reported a decrease in faba bean BNF nitrogen yields from 155 to 94 kg N ha^{-1} when weeds were present and found that increasing planting density (PD) two-fold times could decrease weed biomass by 53%, therefore allowing faba bean to fix more N_2 and sufficiently supply N to the following wheat crop. Similarly, Danso et al. (1987) found a decrease in faba bean BNF of 79 to 71 kg N ha^{-1} when faba bean was intercropped with barley. Overall, it appears that BNF and %Ndfa by faba bean is sensitive to increased weed or crop density but unlike BNF, %Ndfa increased as plant density increased due to the increased competition for uptake of soil N forcing faba bean to derive more N from the atmosphere (Strydhorst et al., 2008; Danso et al., 1987).

The addition of fertilizer is a common management factor that often affects levels of BNF and %Ndfa by most pulses but has varying effects depending on the rate of fertilizer and what mineral nutrients are applied. In a growth chamber experiment conducted many years ago, Richards and Soper (1979) found that faba bean did not respond to N fertilizer when grown in N-deficient soil and that adding N fertilizer decreased BNF proportional to the amount of N fertilizer added. Faba bean could still obtain 42% of its total required N through fixation when the highest amount of fertilizer N was added but was able to fix 83% of its total required N and take up the remaining required N from soil N when no fertilizer was added (Richards and Soper, 1979). Similar results were found in a field study in Manitoba by Richards and Soper (1982), where the addition of N fertilizer decreased BNF by faba bean in all but one trial. In a field experiment in Austria by Hardarson et al. (1991), %Ndfa by faba bean was 85% when the lowest rate of N fertilizer was applied (20 kg N ha^{-1}) and %Ndfa decreased to 43% when the highest rate of N fertilizer was applied (400 kg N ha^{-1}). Richards and Soper (1982) observed that in the trial where added N fertilizer did not decrease BNF by faba bean, it was because BNF did not occur due to high available inorganic soil N levels, which was discussed in the previous section.

Though the addition of N fertilizer often affects BNF and %Ndfa by legumes in a negative way, similar to how high levels of available inorganic soil N negatively affect BNF and %Ndfa, studies have found that faba bean is more tolerant to added N fertilizer when compared with other pulses (Chalifour and Nelson, 1987; Hardarson et al., 1991). This is why BNF and %Ndfa in faba bean will often be higher than BNF and %Ndfa by other pulses in conditions where high soil N levels are present or where high amounts of N fertilizer are added.

Due to the large energy requirements involved in BNF and the role of phosphorus (P) in energy transfer in the plant, P can be a significant growth limiting factor for faba bean and other pulse crops in many soils (Agegnehu and Fessehaie, 2006). Legume crops are negatively affected by low P availability or P deficiency due to the amount of P used by legume nodules during BNF and the higher amounts of P required by N_2 fixing crops compared to non-fixing crops (Vance, 2001; Olivera et al., 2004). However, few studies have examined the response of BNF in faba bean to P fertilization.

2.4 Genetic, Environmental and Management Influences on Faba Bean Nutrition and Yield

2.4.1 Genetic and environmental influences

Much like the environmental, edaphic and management factors affect the BNF and %Ndfa by faba bean and other pulses, similar factors influence faba bean yield and nutrition. Genetic factors such as cultivar affect faba bean yield and therefore nutrient content and requirement. However, the direct influence of these factors depends on the environmental conditions, especially precipitation and temperature, and edaphic factors such as soil fertility (Carranca et al., 1999; Hossain et al., 2017). From the results of Hossain et al. (2017) in Swift Current, Saskatchewan, environmental conditions were identified as dominant factors influencing BNF and yield performance and explaining differences among individual pulse cultivars. These findings underscore the importance of selecting the appropriate cultivar for a specific environment in order to efficiently utilize BNF and achieve optimal yield (Hossain et al., 2017). In Manitoba, Keatinge and Shaykewich (1977) observed that differences in soil moisture and ambient temperature affected both faba bean yield and nutritional attributes such as nitrogen and protein content. More specifically, higher ambient temperatures especially during faba bean flowering caused premature pod formation thus decreasing yield potential (Keatinge and Shaykewich, 1977). Similarly, other studies have observed that BNF, pulse seed N, protein content and yield are impacted by the growth conditions and environmental stresses that the pulse plant is exposed to (Hossain et al. 2017, 2018; Bourion et al., 2010). Reflecting the high moisture requirements of faba bean, Strydhorst et al. (2008) observed higher faba bean yields in areas where the crop experienced greater precipitation in a study in Alberta. Timing of precipitation is also recognized as important. Denton et al. (2017) observed the benefit of early precipitation on faba bean grain yield in a field research trial in Australia, which was attributed to the effect of a higher amount of BNF. In contrast, Bueckert et al. (unpublished) observed that N accumulation increased as moisture increased, but that yield did not increase significantly.

2.4.2 Management influences

2.4.2.1 Effect of fertilization on faba bean

Though N fertilization can influence faba bean growth, it does not have the same effect on faba bean yield and nutrient content as it has on BNF and %Ndfa by pulses. Contrary to the negative effects that fertilization had on BNF and %Ndfa in the study by Richards and Soper (1982), faba bean seed protein content was unaffected by all lower rates of N fertilizer applied and was significantly increased by the application of 300 kg N ha^{-1}. Faba bean seed yields were unaffected by all treatments in the study, including rate of fertilizer N applied at seeding (up to 300 kg N ha^{-1}), application type (broadcasted or with seed), application timing (full bloom or mid pod-fill) and amount of available soil N (NO_3) present (Richards and Soper, 1982). Similar results were found in a field study in Austria by Hardarson et al. (1991), where N fertilizer treatments did not affect total N and dry matter yield of faba bean. In a field study in Saskatchewan by Henry et al. (1995), neither placement or rate of N fertilizer affected faba bean plant stand, which often directly influences yield.

There are relatively few studies on responses of faba bean to P fertilization on the prairies. However, the effect of P fertilization on faba bean was assessed in two studies, roughly 20 years apart, but with similar assessments and results. Effect of P fertilizer rate and placement were assessed for lentil, pea and faba bean in a three-year field study in Saskatchewan by Henry et al. (1995) and more recently on faba bean alone in 2015 by the Indian Head Agricultural Research Foundation (IHARF) (SPG, 2018). Plant establishment was not affected by P placement or P fertilizer rate in either study, but side-banded P was the preferred placement for faba bean in the study by Henry et al. (1995), even though it was the least sensitive crop to seed-placed P. Henry et al. (1995) observed that the P placement and P fertilizer rate did not affect grain yield significantly, though faba bean grain yield was more responsive to increasing P fertilizer rates than lentil and pea grain yield. Indian Head Agricultural Research Foundation found that increasing P fertilizer rate significantly increased faba bean yield, though yield increases were dependent on the conditions of the year and location (SPG, 2018). Grain P concentration increased when rate of P fertilization increased at two of the three sites in the study by Henry et al. (1995), though grain protein concentration was not affected by rate of P fertilizer and neither grain P concentration or grain protein concentration were affected by P fertilizer placement. Grain P concentration and grain protein concentration were not assessed in the study conducted by IHARF. Overall, the results of the two studies showed that P fertilization rate can increase grain yield and grain P concentration under certain conditions, but P fertilizer placement does not have a large effect on faba bean yield or nutrient concentration.

Though many management factors are identified that affect BNF, %Ndfa, nutrition and yield of faba bean, it is obvious that little information is available in the Canadian prairies. Specifically, there is limited information on how fertilization with nutrients other than N affects faba bean nutrition, BNF and yield in Saskatchewan. This thesis addresses that research gap along with providing new information on the yield, macro- and micronutrient uptake and BNF of different faba bean cultivars grown in different soil-climatic regions of Saskatchewan.

3. Yield and uptake of nitrogen and phosphorus by faba bean in Saskatchewan, Canada as affected by cultivar and fertilization

3.1 Preface

This chapter reports on the effects of fertilizer treatment, cultivar and site location on faba bean yield, nitrogen (N) and phosphorus (P) uptake and partitioning among yield components for four faba bean cultivars with two fertilizer treatments at four field site locations across south-central Saskatchewan in 2016 and 2017. In addition, the effects of P fertilization rate and cultivar on faba bean yield, biological nitrogen fixation (BNF), N and P uptake and partitioning were included for two faba bean cultivars with three rates of added P fertilizer in a glasshouse pot study in 2017. Faba bean straw and grain yield, N and P concentration and uptake were measured in the field study and faba bean above- and belowground yield, N and P concentration and uptake and aboveground %Ndfa by faba bean were measured in the glasshouse study.

3.2 Abstract

More pulse crops like faba bean (*Vicia faba* L.) are being included in crop rotations on the prairies, and faba bean production acres have increased in Saskatchewan. Introduction of new cultivars with increased yield potential, biological nitrogen fixation (BNF) and disease resistance to *Aphanomyces eueiches*, have contributed to adoption of faba beans by growers. Unfortunately, there is little to no information on nutrient requirements of modern faba bean cultivars, or on the effect of fertilization of faba bean grown under prairie conditions. To address these identified gaps, four zero tannin faba bean cultivars were grown in a two-year field study in 2016 and 2017 at four site locations representing the Dark Brown, Black and Dark Grey soil-climatic zones of Saskatchewan. Two different fertilizer treatments, 1) unfertilized, and 2) fertilized with nitrogen (N), phosphorus (P), potassium (K) and sulfur (S), were used. A glasshouse study was also conducted in 2017 with two of the four faba bean cultivars used in the field study in order to address how P fertilization of faba bean may influence growth and the proportion of nitrogen derived from atmosphere (%Ndfa) through BNF. In the 2016 and 2017 field study, average faba bean grain yield (5,283 kg ha^{-1}) and average harvest index (HI) (36-63%) were generally similar to, or greater than, faba bean yields reported in past prairie field studies. Average grain N uptake (117-300 kg N ha^{-1}) and P uptake (~15-35 kg P ha^{-1}; 34-80 kg P_2O_5 ha^{-1}) were greater than average straw N and P uptakes. Faba bean yield was not significantly affected by cultivar, fertilization or site location, but HI was affected by cultivar and site location, and N and P uptake were significantly affected to varying degrees by all three effects. Assuming ~ 88 %Ndfa obtained in the glasshouse study, and ~ 230 kg N ha^{-1} of uptake observed in aboveground biomass (grain + straw) in the field experiments, an estimated 200 kg N ha^{-1} was potentially contributed from BNF by faba bean.

3.3 Introduction

Commercial faba bean (*Vicia faba* L.) production has been reported in western Canada since 1972 (Graf and Rowland, 1987), but interest in including faba bean as a grain legume (pulse) component of modern crop rotations has increased, and the area of faba bean production has grown. This can be at least partially attributed to the N related and non-N related benefits that faba bean and other pulse crops contribute to cropping systems. Pulses like faba bean are both economically and environmentally beneficial. Faba bean have greater disease resistance to *Aphanomyces eueiches* than other pulse crops, such as pea and lentil, and can reduce the need for N fertilizer for themselves, and for succeeding crops in rotation due to their ability to form symbiotic relationships with *Rhizobium* bacteria that carry out biological nitrogen fixation (BNF) of atmospheric N (N_2) (Walley et al., 2007; Jensen et al., 2010). For example, faba bean was able to reduce the need for N fertilizer in succeeding cereal crops in a five-cycle rotation study in northeastern Saskatchewan conducted by Wright (1990b) from 1982 to 1987. In that study, the N fertilizer replacement value of faba bean in rotation was calculated to be 120 kg N ha^{-1}. In a greenhouse experiment in western France conducted by Dayoub et al. (2017) in 2014, faba bean was able to reduce its uptake of soil N by fixing N_2 at the same time. As important as these N related benefits are, non-N related benefits of faba bean and other pulses also improve yield of subsequent crops through reduction of diseases, increasing availability of other essential macronutrients, such as phosphorus (P), potassium (K) and sulfur (S) (Stevenson and van Kessel, 1996; Xie et al., 2018), and increasing microbial activity, diversity (Lupwayi and Kennedy, 2007; Jensen et al., 2010), nutrient availability and moisture in soil (Peoples et al., 2009; Williams et al., 2014).

As more faba bean acres are included in crop rotations in western Canada, more information is needed on the nutrient requirements of faba bean crops, including uptake and partitioning among yield components. Of particular interest is the contribution of BNF as this represents an external input to the cropping system. For example, increased BNF can be beneficial to pulse crops and crops following pulses in rotation, but studies have found that much of the N_2 fixed by faba bean and other pulse crops often accumulates in high-protein pulse grain and is removed when grain is harvested, therefore a smaller amount of N content is left behind in plant residue than is initially fixed (Beck et al., 1991; Peoples et al., 2009;

Walley et al., 2007). It is important to know how nutrients, especially N and P, are partitioned between pulse straw and grain to better assess how the nutrient content of the grain removed and the remaining components will affect crops following the pulse crop in rotation (Xie et al., 2018). Nutrient content of pulse roots and other root components should also be considered when assessing nutrient content of pulses, but is often overlooked, which can lead to an underestimation of the amount of N contributed to pulses through BNF (Walley et al., 2007).

Faba bean has shown greater BNF capabilities, seed yield and grain N uptake compared to other pulses (Dayoub et al., 2017; Hossain et al., 2018), but there are limited recent faba bean field studies in western Canada. Furthermore, the faba bean yield and nutrient data that is available globally and in western Canada is often based on irrigated faba bean crops (Walley et al., 2007; Peoples et al., 2009), with data available only from a limited number of cultivars (Hossain et al., 2017) or observations (Walley et al., 2007). Recent field studies in Saskatchewan that have measured BNF in faba bean (e.g. Hossain et al., 2017) have considered only one faba bean cultivar, and faba bean was not included as one of the pulses studied by Xie et al. (2018). Results of these studies and others support the concept that the benefits of pulses and BNF contributions do vary among species, cultivar, environment and management practices (Malhi et al., 2008; Hossain et al., 2017; Xie et al., 2018). However, no recent studies have been conducted to assess different faba bean cultivars grown in different site locations, especially under dryland conditions. The purpose of the thesis research described in this chapter is to provide new information on yield, uptake and removal of the macronutrients N and P, along with BNF and P fertilizer response in faba bean cultivars grown at different site locations (soil-climatic conditions) in Saskatchewan. This information should be useful to growers who include or plan to include faba bean in their crop rotations.

Nitrogen and phosphorus are considered the first and second most influential nutrients in crop growth, respectively (Anglade et al., 2015; Li et al., 2010). Therefore, measurements to quantify N and P removal by a crop are essential to fully assess the influence of any crop, including faba bean, on soil fertility and nutrient requirements in a sustainable cropping system. This chapter aims to follow the three objectives and address the three hypotheses stated in Chapter 1. The results reported in this chapter from the two-year field study conducted in 2016 and 2017 at four site locations situated in the Dark Grey, Black and Dark Brown soil-climatic zones in south-central Saskatchewan, with four zero tannin faba bean cultivars and two fertilizer treatments: unfertilized, and fertilized with nitrogen (N), phosphorus (P), potassium (K) and sulfur (S), followed objective (a) and addressed hypothesis (a). Faba bean assessment in this study included measuring yield, concentration and uptake of N and P in faba bean straw and grain. Comparisons were made between faba bean yield, uptake and N and P crop removal measurements in the current field study and measurements of faba bean and other pulse crops, including soybean, lentil and pea, using data from recent studies in western Canada. Effects of site location, cultivar and fertilizer treatment on faba bean were also considered.

To add insight into faba bean N and P nutrition, a glasshouse study was conducted in Saskatoon in 2017 with two faba bean cultivars to determine the effect of three applied P fertilizer rates on faba bean above- and belowground biomass yield, N and P uptake and BNF using ^{15}N-labelled urea and the ^{15}N isotope dilution method to determine proportion of nitrogen in the plant derived from the atmosphere (%Ndfa). The glasshouse study followed objective (b) to address hypothesis (b) in this chapter. Objective (c) and hypothesis (c) were addressed in both the field and glasshouse study results in this chapter.

3.4 Materials and Methods

3.4.1 Field nutrient uptake trials

3.4.1.1 Site descriptions and experimental design

The field studies were conducted in 2016 and 2017 at four sites in Saskatchewan (SK) near Meath Park, Rosthern, Saskatoon and Outlook, in fields that were also used for faba bean breeding trials of the Crop Development Centre at the University of Saskatchewan. The locations were representative of typical faba bean growing regions in the Dark Grey (Meath Park), the Black (Rosthern) and the Dark Brown (Saskatoon and Outlook) soil-climatic zones of Saskatchewan (Fig. 3.1).

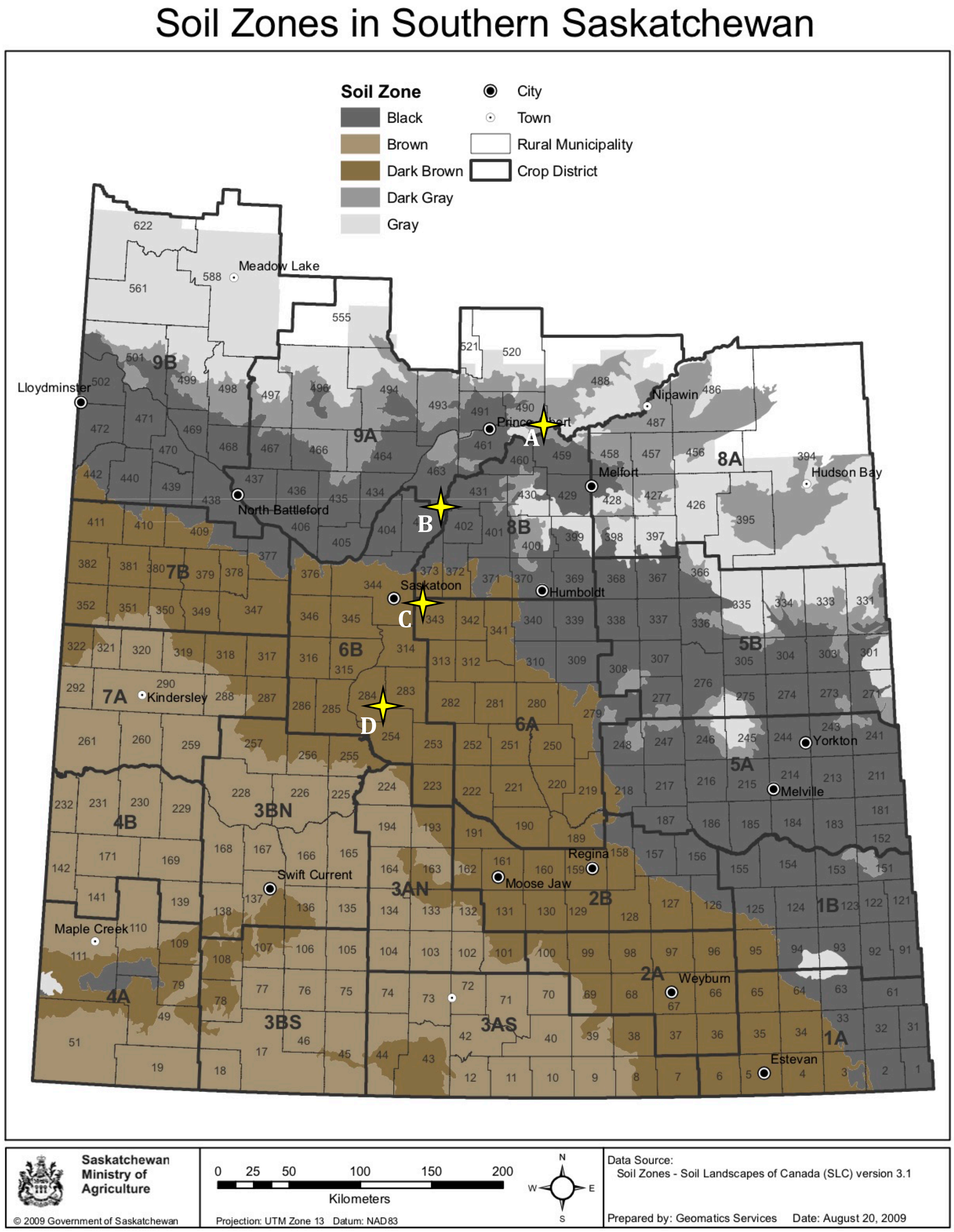

Fig. 3.1. The four faba bean field site locations in southern Saskatchewan, (A) Meath Park, (B) Rosthern, (C) Saskatoon, (D) Outlook (Government of Saskatchewan, 2009).

The site at Outlook was irrigated while the others were dryland. The faba bean crop at the 2016 Outlook site experienced high, damaging winds early in the season, and the faba bean crop at the 2017 Outlook site was destroyed by a hail storm in July. Information and results from the 2017 Outlook site will not be covered further in this thesis. The legal land location, soil associations and soil texture for each site are shown in Table 3.1. A different area was chosen in the same quarter section or in an adjacent quarter section as the site location each year over two years of the study. Bouyoucos hydrometer analysis (Thien and Graveel, 2003) was conducted to determine soil texture at each site.

Table 3.1. Description of the four 2016 and 2017 field site locations.

Year	Site location	Legal land location	Soil association†	Soil texture
2016	Meath Park	NE-29-49-24-W2	Orthic Nisbet/ Orthic Shellbrook	Sandy loam
	Rosthern	SW-07-43A-02-W3	Hamlin Orthic Black/ Blaine Lake Orthic Black	Silty loam
	Saskatoon	SE-36-35-04-W3	Elstow Orthic Dark Brown	Silty loam
	Outlook	NW-12-29-08-W3	Asquith Orthic Dark Brown	Loamy sand
2017	Meath Park	NE-28-49-24-W2	Blaine Lake Orthic Black/ Hoey Orthic Black	Loam
	Rosthern	NW-07-43A-02-W3	Hamlin Orthic Black/ Blaine Lake Orthic Black	Loam
	Saskatoon	SE-36-35-04-W3	Elstow Orthic Dark Brown/ Elstow Eluviated Dark Brown	Silty loam

† University of Saskatchewan, 2017.

A completely randomized split-plot design was used in the study. Fertilizer treatment was the main factor at each site with cultivar as the split factor. Two fertilizer treatments were applied to four cultivars and replicated four times for a total of 32 plots at each site. The plots were 3.7 m by 0.8 m with an interplot space of 0.8 m and a block pathway space of 1.8 m. There was no fertilizer applied in the first treatment and the second treatment was a N, P, K, S blend applied as potassium sulfate (K_2SO_4) (0-0-44-17) at 100 kg ha^{-1} and monoammonium phosphate (MAP) (11-52-0) at 100 kg ha^{-1}. The application of the blanket blend was intended to provide ample P, K and S for faba bean growth along with a small amount (11 kg N ha^{-1}) of starter N. The fertilizer blend was broadcast and incorporated with light tillage during seed-bed preparation prior to seeding.

Four zero tannin faba bean cultivars were provided and seeded by the Crop Development Centre at the University of Saskatchewan. Two smaller (CDC Snowdrop, 219-16) and two larger (Snowbird, Tabasco) seeded cultivars (Table 3.2), were cleaned and treated as a batch with Insure® Pulse (BASF Canada Inc., 2015) at the recommended rate before being exposed to UV light for 8 h to test and ensure all seeds were zero tannin. Faba bean seeds were double inoculated. Nodulator®FB Peat inoculant (*Rhizobium leguminosarum* biovar *viciae)* (BASF Canada Inc., 2015) was applied to faba bean seed immediately prior to seeding at a higher than recommended rate and TagTeam™ granular faba bean inoculant (Monsanto Company, 2015) was also applied along with faba bean seed at the time of seeding at the recommended label rate. A small plot seeder with 2.54 cm (1") disk openers and 30.48 cm (12") row spacing was used to seed faba bean plots at a seeding rate of 43 seeds m^{-2} (4 seeds ft^{-2}) to a depth of 5.08 cm (2"). In 2016, Saskatoon, Meath Park, Rosthern and Outlook sites were seeded into cultivated cereal residue on April 28, May 5, May 6 and May 17, respectively. In 2017, Saskatoon, Meath Park and Rosthern sites were seeded into cultivated cereal residue on May 17, May 18 and May 18, respectively. Care was taken to seed plots slowly, especially with larger seed varieties, to decrease the risk of plugging the seeder and ensure a uniform seeding rate was achieved for each plot.

Table 3.2. Four zero tannin faba bean cultivars used in the field study in 2016 and 2017.

Cultivar	**Breeder**	**Seed Weight†**	**Days to Maturity†**
		g 1000^{-1}	
CDC Snowdrop	CDC University of Saskatchewan	335	104
219-16	CDC University of Saskatchewan	360	102
Snowbird	Limagrain Nederland	495	104
Tabasco	NPZ Lemke	530	106

† Government of Saskatchewan, 2016.

Fall application rates of 27.9 kg ha^{-1} of Edge® (granular ethafluralin) (Gowan Company, L.C.C., 2016) and 69.2 mL ha^{-1} of Pursuit® (imazethapyr) (BASF Canada, Ltd., 1995) were applied to plots in fall 2015 and fall 2016 at the Saskatoon, Meath Park and Rosthern sites.

In spring 2016, Roundup Transorb® (glyphosate) (Monsanto Canada Inc., 2015) was applied alone at 2.5 L ha^{-1} to the Meath Park and Rosthern plots on May 10, and together with Authority® (sulfentrazone) (FMC Corporation, 2016) at 292 mL ha^{-1} on May 14 on the Saskatoon plots. Edge® was applied on May 13 at the Outlook site in spring 2016 at a rate of 8.9 kg ha^{-1}, followed by an application of Heat® LQ (saflufenacil) (BASF Canada Ltd., 2016) at 146 mL ha^{-1} and Roundup Transorb® at 2.5 L ha^{-1} on May 14.

High weed pressure was observed during the 2016 growing season and warranted foliar herbicide application at all four sites. A rate of 1.0 L ha^{-1} Viper® ADV (imazamox and bentazon) (BASF Canada Ltd., 2016) with an additional 358 mL ha^{-1} of Basagran® (bentazon) (BASF Canada Ltd., 2016) was applied at all four sites. Application occurred at Saskatoon on June 1 and at Outlook on June 21, and because blister beetle pressure at the Meath Park and Rosthern sites warranted an insecticide application, Sevin® XLR (carbaryl) (Tessenderlo Kerley, Inc., 2012) was applied with Viper® ADV and Basagran® on June 15. Rates of 1.18 L ha^{-1} Axial® BIA (pinoxaden) (Syngenta Canada Inc., 2016) and 185 mL ha^{-1} Centurion® (clethodim) (Bayer CropScience Inc., 2015) were applied together at Saskatoon (June 13), Outlook (June 14), and Meath Park and Rosthern (June 22). An additional application of 1.7 L ha^{-1} Basagran® was applied to the Meath Park and Rosthern sites on June 29. Hand weeding was implemented, especially in Meath Park plots, to control weeds later in the season until plots were hand harvested in late August 2016.

In spring 2017, Roundup® (glyphosate) was applied at 2.5 L ha^{-1} with Authority® (sulfentrazone) at 292 mL ha^{-1} on May 24 at the Meath Park and Rosthern plots. To maintain plots during the growing season, 1.18 L ha^{-1} of Axial® BIA (pinoxaden) and 185 mL ha^{-1} of Centurion® (clethodim) were applied together at Meath Park on June 8. A rate of 1.0 L ha^{-1} of Viper® ADV (imazamox and bentazon) with an additional 358 mL ha^{-1} of Basagran® (bentazon) was applied at Rosthern and Meath Park (June 16), and Saskatoon (June 19) sites. After finding crop damage due to blister beetles, 86 mL ha^{-1} of Matador was applied at Rosthern, Meath Park and Saskatoon sites on June 25, June 26 and July 7, respectively. Later in the season, 1.18 L ha^{-1} of Axial® BIA (pinoxaden) and 185 mL ha^{-1} of Centurion® (clethodim) were applied together at Rosthern and an additional application of 1.7 L ha^{-1} Basagran® was applied to the Meath Park site on July 5. Chocolate spot (*Botrytis cinerea*) was observed in both years but it was not deemed sufficiently severe to warrant fungicide application.

3.4.1.2 Climate data

Climate data is summarized in Table 3.3 for the 2016 and 2017 field study growing seasons (May-August). The climate data is based on the meteorological data collected from Environment Canada weather stations nearest to the four research site locations in

Saskatchewan (Environment Canada). Monthly cumulative precipitation in the 2016 growing season was similar to historical (1981-2010) cumulative precipitation at the Saskatoon, Rosthern and Meath Park site locations, and was almost 2x greater than the historical cumulative precipitation at the Outlook site location. The growing season in 2017 was drier than in 2016, as shown by a lower monthly cumulative precipitation compared to 2016 and to the historical cumulative precipitation for all four site locations (Table 3.3). Mean daily maximum temperatures in both the 2016 and 2017 growing seasons were similar to or slightly greater than the historical mean daily maximum temperatures.

Table 3.3. Monthly precipitation and mean daily maximum temperature during the growing season (May-August) in 2016 and 2017, as compared to historical (1981-2010) mean (HM) data at the four site locations in 2016 and 2017 (Environment Canada).

Site	Month	Precipitation			Temperature		
		2016	2017	HM†	2016	2017	HM†
			mm			°C	
Meath Park	May	29.8	64.2	44.7	20.3	18.2	17.5
	June	63.0	64.8	68.6	23.9	21.7	21.8
	July	88.8	51.4	76.6	24.8	25.3	24.3
	August	78.8	12.1	61.6	23.2	24.9	23.4
	Sum/Mean‡	260.4	192.5	251.5	23.1	22.5	21.8
Rosthern	May	41.6	46.3	43.0	21.4	19.9	18.2
	June	49.7	30.9	65.8	24.7	23.5	22.4
	July	58.6	25.5	60.3	25.3	27.5	25.3
	August	70.2	25.2	42.6	23.3	26.0	24.9
	Sum/Mean	220.1	127.9	211.7	23.7	24.2	22.7
Saskatoon	May	42.6	48.5	36.5	21.7	20.4	18.5
	June	46.8	25.4	63.6	25.0	23.0	22.6
	July	76.9	28.0	53.8	25.1	27.5	25.7
	August	-§	-	44.4	-	-	25.2
	Sum/Mean	166.3	101.9	198.3	23.9	23.6	23.0
Outlook	May	55.7	-	42.6	21.1	-	18.4
	June	45.8	-	63.9	24.2	-	22.5
	July	194.6	-	56.1	24.2	-	25.6
	August	69.9	-	42.8	23.1	-	25.0
	Sum/Mean	366.0	-	205.4	23.2	-	22.9

† Historical (1981-2010) mean data from the nearest Environment Canada Meteorological Station to each of the four site locations.

‡ Precipitation data denotes cumulative precipitation from May to August and temperature data denotes mean monthly maximum temperature during this period.

§ Data not reported.

3.4.1.3 Soil and plant sampling and analyses

Soil analysis was conducted in 2016 and 2017 at each site in April before seeding and again in the fall in September after harvest. Main soil properties for the 0-15 cm soil depth are shown in Table 3.4 and additional available soil micronutrient (Mn and B) values can be found in Table A.1. In the spring, soil cores were taken with a dutch auger (3 cm dia.) at each site along a 10 point transect set out across the plot area just after marking and before the fertilizer treatments were applied. Cores were taken at depths of 0-15, 15-30 and 30-60 cm and samples were composited for each depth The soil cores taken after harvest to measure the soil available N and P were sampled with the same auger at the same depths as the spring core samples. Two core samples were taken from each plot at all three depths in the fall post-harvest soil sampling, one from between seed rows and one in a seed row. Soil samples were kept frozen until they were air dried, sieved (<2 mm) and analyzed. Total available macro- and micronutrients were measured in each spring soil sample, along with organic carbon (OC), pH and electrical conductivity (EC). No micronutrient deficiencies or significant macronutrient deficiencies were identified at the sites according to the soil test and fertilize recommendations (ALS Labs Saskatoon, SK). Organic carbon (%) measurements were considerably lower at the Outlook site compared to other sites, likely due to the sandy, coarse soil

Table 3.4. Pre-seeding soil properties (n=10) in the 0-15 cm soil profile at the four 2016 and 2017 field site locations. Soil samples were bulked to provide a composite sample. Nutrients (NO_3, P, K, SO_4, Cu, Zn and Fe) are extractable, available forms measured using methodologies described in the text.

Site location	**pH**	**EC†**	**OC†**	**NO_3**	**P**	**K**	**SO_4**	**Cu**	**Zn**	**Fe**
		dS m^{-1}	**%**	**-----kg ha^{-1}-----**						
---***2016***---										
Meath Park	6.3	0.1	2.0	4.3	54	484	6.0	0.7	4.0	128
Rosthern	6.7	0.1	3.1	15.1	27	299	8.1	1.5	3.4	123
Saskatoon	6.4	0.1	2.3	18.8	47	868	8.8	1.6	3.3	125
Outlook	7.6	0.1	0.9	5.1	31	282	3.9	0.5	1.0	13
---***2017***---										
Meath Park	6.7	0.1	4.0	13	35	633	7.9	2.1	7.8	269
Rosthern	6.8	0.2	-‡	18	27	476	6.7	1.9	5.3	185
Saskatoon	7.9	0.3	2.4	36	65	1111	12.8	2.1	4.6	123

† EC = electrical conductivity; OC = organic carbon.

‡ Data not available.

Total OC concentration was measured using a LECO C-632 combustion carbon analyzer (LECO Corporation, St. Joseph, MI, USA). Soil pH and electrical conductivity (EC) were measured with a Beckman pH and an EC meter in a 1:2 soil:water suspension (Nelson and Sommers, 1982). Soil nitrate (NO_3) and sulfate (SO_4) were extracted from soil samples taken at all three depths with 0.01M $CaCl_2$ (Houba et al., 2000). Available phosphorus (P) and potassium (K) from soil samples at the 0-15 and 15-30 cm soil depths were extracted using a modified Kelowna procedure (Qian et al., 1994). A 0.005M diethylene-triamine-penta acetic acid (DTPA) solution was used to extract available Cu, Zn and Fe in soil (Lindsay and Norvell, 1978) and a hot water extraction was used to measure B.

At maturity, faba bean plants were hand harvested (two 1 m row lengths) at 5 cm above the soil surface from the middle row of each plot. Samples were air dried and weighed to measure total aboveground biomass before they were threshed. Grain and straw were separated, and grain samples were weighed before both grain and straw samples were ground in preparation for elemental analysis. Grain yield (kg ha^{-1}) was determined by threshing, and straw yield was calculated by subtracting the grain yield from the total aboveground biomass. A sulphuric acid and hydrogen peroxide digestion (Thomas et al., 1967) was used to prepare grain and straw samples for analysis to measure concentrations of N and P. The N and P uptake (kg ha^{-1}) in the straw and grain was calculated by multiplying straw and grain yield by N and P concentrations, respectively.

A Technicon Auto-analyzer II segmented flow automated system (Technicon Industrial Systems, Tarrytown, NY, USA) was used to colorimetrically analyze soil extracts and straw and grain digests to measure available N and P in soil and N and P concentration in straw and grain. An Agilent™ Model 200 Atomic Absorption (AA)/Flame Emission (FE) Spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA) was used to measure available K, Ca, Mg, Cu, Zn and Fe in soil sample extracts. Sample weights were increased for micronutrient analysis to ensure available micronutrients were within detection limits on the atomic absorption spectrometer. An Agilent™ Microwave Induced Plasma Emission Spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA) was used to measure S and B from soil extracts.

3.4.1.4 Statistical analyses

Data were analyzed as a split-plot experimental design with the PROC GLIMMIX procedure of SAS 9.4 for Windows (Littell et al., 2006; SAS Institute, 2013). A significance level of 0.05 was used unless otherwise stated. The effects of replicate (nested in site) and replicate by treatment (main plots; nested in site) were considered random. The effect of site, cultivar, and treatment were considered fixed. The RANDOM statement with a _RESIDUAL_ effect was used to model residual heterogeneity. The corrected Akaike's Information Criterion (AICc) was used to confirm the benefit of modeling variance heterogeneity for all analyses. The SLICE statement was used to facilitate comparisons for interactions. The LINES option with the LSMEANS and SLICE statement was used to complete means comparisons.

3.4.2 Glasshouse faba bean phosphorus fertilization response study

3.4.2.1 Experimental design

Faba bean were grown in pots from June to August 2017 in a glasshouse near the University of Saskatchewan field laboratory on Preston Avenue to evaluate the yield and BNF response of two cultivars of faba bean to P fertilization on a P deficient soil. A completely randomized design (CRD) was used. Three P fertilizer treatments, 0, 20, 40 kg P_2O_5 ha^{-1}, were applied as monocalcium phosphate (Triple Super Phosphate; 0-45-0) and two zero tannin faba bean cultivars: CDC Snowdrop (small seed) and Snowbird (large seed) were grown, to establish whether the effect of treatment is similar in cultivars with contrasting seed weight. Seed weight can also affect the contribution of P stored in the seed to early P nutrition of the seedling. The treatments were replicated four times and one pot of non-fixing reference crop (Waskada CWRS wheat) was included for every faba bean treatment in the experiment, as described in Hardarson and Danso (1990), for a total of 48 pots. Four kg of soil was used in each 5 L plastic pot and hand watered each day to maintain the soil at field capacity. A P deficient (MK extractable P = 6 ppm) sandy loam Chaplin association surface (0-15cm) soil was collected for the study from south-central Saskatchewan in late April of 2017. A sandy texture was desired to facilitate separation of roots from the potting soil.

Phosphorus fertilizer treatments were applied along with a basal application of K and S (100 kg ha^{-1} K_2SO_4) at a depth of 2.5 cm, just before the faba bean seeds were planted at a depth of 1.3 cm. Seeds were inoculated with Nodulator®FB Peat inoculant (*Rhizobium leguminosarum* biovar *viceae)* (BASF Canada Inc., 2015) before seeding and pots were watered after seeding. Pots were then watered to field capacity every day for the duration of the study and were rearranged randomly every week to ensure the conditions of a CRD was maintained. Mean hourly air and soil temperature were recorded using Hobo H8 Pro Series probes (Onset, Bourne, MA, USA) throughout the duration of the study. Mean daily maximum air temperature was calculated for June (29.8 °C), July (34.3 °C) and August (33.9 °C) and mean daily soil temperature was calculated for June (18.4 °C), July (21.1 °C) and August (20.0 ^{0}C).

After emergence, plants were thinned to two per pot. At the three to four leaf stage of faba bean and the three to five leaf stage of wheat, ^{15}N-labelled urea fertilizer (10 atom % ^{15}N enrichment – randomly labelled) was dissolved in deionized water as described by Knight (2012) and applied to the soil in a liquid form at an equivalent rate of 5.6 kg N ha^{-1} (5 lb N ac^{-1}). Caution was taken to ensure the soil was not excessively watered and the ^{15}N-labelled urea remained in the soil and did not run out of the pot after it was applied. Saucers were placed under each pot in case the ^{15}N-labelled urea leached out of the pot if the soil was watered in excess.

3.4.2.2 Soil and plant sampling and analyses

Soil analysis (ALS Labs Saskatoon, SK) was conducted in April 2017 before seeding. Results of the analysis are shown in Table 3.5. Faba bean plants were hand harvested from each pot at maturity, air dried and weighed to measure total aboveground biomass. Belowground plant material (roots and nodules) and soil were preserved by freezing them immediately after aboveground plant material was harvested. Prior to analysis, the soil and belowground plant material from each pot was thawed, separated by dry sieving, and a subsample of the soil was taken before roots were washed. Roots and nodules were then separated, nodules were counted and categorized by shape, and the roots and nodules were air dried before being weighed separately. Total belowground biomass was calculated by adding root and nodule weight together.

Table 3.5. Pre-seeding properties of soil used in the glasshouse faba bean phosphorus (P) fertilization response study in 2017.

Texture	Sand	Silt	Clay	pH	EC†	OC†	NO_3	P	K	SO_4	Cu	Zn	Fe
	%	%	%		dS m^{-1}	%	mg kg^{-1}						
Sandy loam	56	26	18	7.8	0.1	0.9	3.7	6.0	223	7.3	0.8	8.7	4.6

† EC = electrical conductivity; OC = organic carbon; nutrients are extractable, available forms measured using methodologies described in the text.

Mass spectrometry analysis was conducted in the Department of Soil Science stable isotope laboratory at the University of Saskatchewan to measure the ^{15}N concentration and %N of above- and belowground plant samples.

Analysis and measurements of N and P concentration and uptake and available NO_3 and P in the soil were completed using the same techniques used in the 2016 and 2017 field studies. Soil nitrate was extracted from soil samples with 0.01M $CaCl_2$ (Houba et al., 2000) and available P was extracted using a modified Kelowna procedure (Qian et al., 1994). A sulphuric acid and hydrogen peroxide digestion at 360^{o} (Thomas et al., 1967) was used to prepare above- and belowground plant samples for analysis to measure concentrations of N and P and a Technicon Auto-analyzer II segmented flow automated system (Technicon Industrial Systems, Tarrytown, NY, USA) was used to colorimetrically analyze soil extracts and above- and belowground plant digests for N and P.

3.4.2.3 Calculations and statistical analysis

Yield was calculated from total aboveground biomass per pot area and N yield was calculated by multiplying %N by total yield. Estimation of the percentage of N derived from the atmosphere (%Ndfa) by faba bean cultivars from the ^{15}N controlled environment P fertilization response study, as well as proportion of N derived from fertilizer (%Ndff) and proportion of N derived from soil (%Ndfs), were calculated according to McAuliffe et al. (1958) and Fried and Middelboe (1977):

$$\%Ndfa = \left(1 - \frac{atom\ \%15N\ excess\ of\ fixing\ crop}{atom\ \%15N\ excess\ of\ non\text{-}fixing\ crop}\right) \times 100 \qquad \text{(Eq. 3.1.)}$$

$$Ndfa\ (kg) = \%Ndfa \times total\ N\ (plant) \qquad \text{(Eq. 3.2.)}$$

It can be noted that atom % ^{15}N excess refers to the ^{15}N content of the sample minus the background of 0.36637 found in N_2.

$$\%Ndff = \frac{atom\ \%15N\ excess\ (plant)}{atom\ \%15N\ excess\ (fertilizer)} \qquad \text{(Eq. 3.3.)}$$

$$Ndff\ (kg) = \%Ndff \times total\ plant\ N \qquad \text{(Eq. 3.4.)}$$

$$Ndfs\ (kg) = total\ plant\ N - Ndfa - Ndff \qquad \text{(Eq. 3.5.)}$$

Estimated %Ndfa and measured total aboveground N yield of field study faba bean were used to estimate BNF contribution using the following equation (Hardarson and Danso, 1990):

$$Amount\ of\ atmospheric\ N\ fixed\ =\ \frac{\%Ndfa\ x\ total\ N\ in\ plant}{100} \qquad \text{(Eq. 3.6.)}$$

Data were statistically analyzed as a CRD experimental design with the PROC GLIMMIX procedure of SAS (Littell et al., 2006; SAS Institute, 2013). A significance level of 0.05 was used unless otherwise stated. The effect of cultivar and treatment were considered fixed. The RANDOM statement with a _RESIDUAL_ effect was used to model residual heterogeneity. The corrected Akaike's Information Criterion (AICc) was used to confirm the benefit of modeling variance heterogeneity for all analyses. The SLICE statement was used to facilitate comparisons for interactions. The LINES option with the LSMEANS and SLICE statement to facilitate means comparisons.

3.5 Results

3.5.1 2016 and 2017 field studies

3.5.1.1 Faba bean yield, nitrogen and phosphorus concentration and uptake

Faba bean yielded well, with mean grain yields from 3,000 - 7,000 kg ha^{-1} (3 - 7 t ha^{-1}) at the four site locations in the 2016 (Fig. 3.2) and 2017 (Fig. 3.3) field studies. Mean yield values for unfertilized and fertilized treatments at each site location in 2016 and 2017 can be found in Table A.2. Straw yields from individual plots ranged from 1,288 - 10,108 kg ha^{-1} in 2016 and 2,536 - 9,028 kg ha^{-1} in 2017, and grain yields ranged from 979 - 9,787 kg ha^{-1} in 2016 and 2,414 - 9,757 kg ha^{-1} in 2017. Yields were lowest at the Outlook site due to adverse growing conditions in 2016, and the site was lost to hail in 2017. The analysis of variance (ANOVA) indicated no significant effect of site location, treatment or cultivar on grain, straw or total faba bean yield in either study year (Table A.3). Partitioning of yield between grain and straw differed with site location and cultivar each year (Fig. 3.2 and 3.3). In 2016, trends showed that mean grain yield was greater than straw yield at Meath Park and Rosthern locations and straw yield was greater than grain yield at the Saskatoon and Outlook site locations. In 2017, straw and grain yields were about equal at all three locations, with grain yield being slightly greater than straw yield at the Rosthern and Saskatoon site locations.

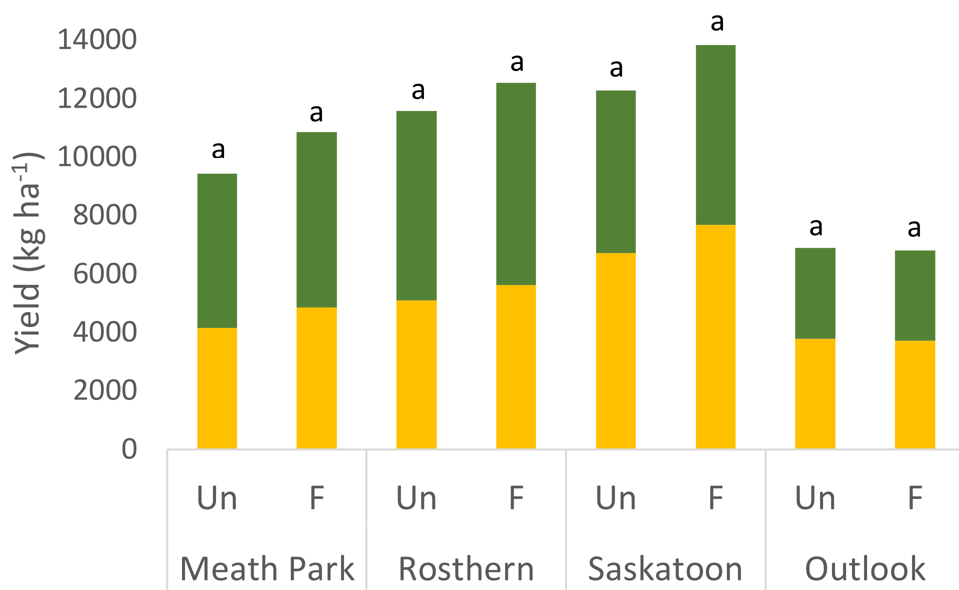

Fig. 3.2. Straw (yellow) and grain (green) yield (n=4) of faba bean at four 2016 field site locations. Un denotes unfertilized and F denotes fertilized treatments. Within a site location, bars with the same letter are not significantly different ($p \geq 0.05$). Note that wind damage occurred during the growing season at the Outlook site.

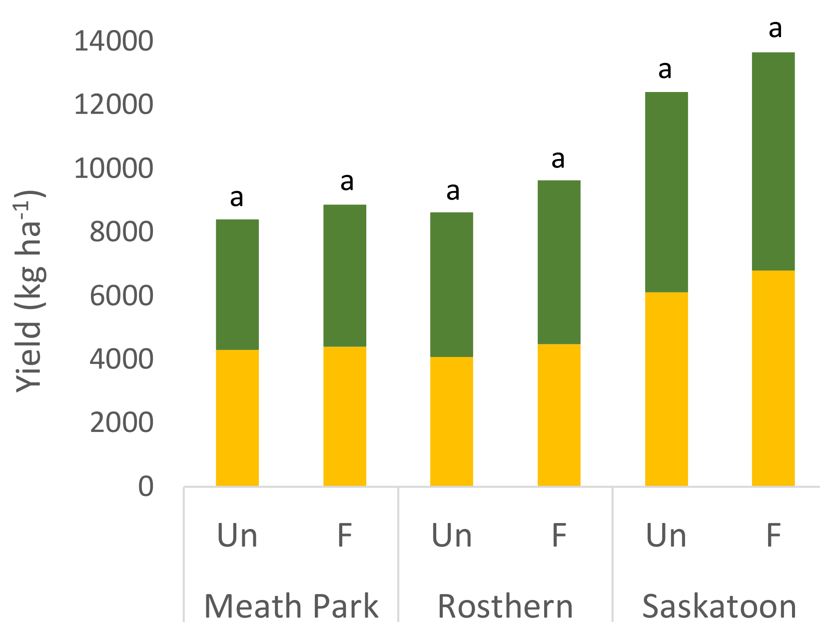

Fig. 3.3. Straw (yellow) and grain (green) yield (n=4) of faba bean at the three 2017 field site locations. Un denotes unfertilized and F denotes fertilized treatments. Within a site location, bars with the same letter are not significantly different ($p \geq 0.05$).

Both site location and cultivar had significant effects on HI in 2016 and 2017 (Table 3.6) and the interaction between site location and cultivar was significant for HI in 2017 (Table A.4). The mean HI of faba bean at the Meath Park (56%) and Rosthern (56%) sites in 2016 were greater than the average HI of faba bean at the Saskatoon (45%) and Outlook (45%) sites in the same year. The cultivar Snowbird had a greater HI than the other cultivars at most site locations in 2016 and along with 219-16 and Tabasco, had a greater HI than CDC Snowdrop at Rosthern and Saskatoon site locations in 2017.

Table 3.6. Mean harvest index (HI = grain yield/grain+straw yield) (n=4) of four faba bean cultivars with two fertilizer treatments at the four 2016 and the three 2017 field study site locations.

Site location	Cultivar	2016	2017
		HI	
		%	
Meath Park	CDC Snowdrop	54 c†	52 a
	219-16	58 b	47 c
	Snowbird	60 a	49 b
	Tabasco	51 d	50 ab
Rosthern	CDC Snowdrop	53 b	49 b
	219-16	58 a	55 a
	Snowbird	59 a	53 a
	Tabasco	53 b	54 a
Saskatoon	CDC Snowdrop	44 bc	47 c
	219-16	45 b	53 a
	Snowbird	49 a	51 b
	Tabasco	41 c	52 ab
Outlook	CDC Snowdrop	43 bc	-‡
	219-16	45 b	-
	Snowbird	49 a	-
	Tabasco	42 c	-

† Within a column, means within a site location followed by the same letter are not significantly different from each other ($p \geq 0.05$).

‡ The 2017 Outlook site faba bean crop was destroyed by hail. Data not available.

As expected, mean faba bean grain N and P concentrations were greater than straw N and P concentrations for both fertilizer treatments in all cultivars across all site locations in 2016 and 2017 (Tables 3.7 and 3.8).

Table 3.7. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial nitrogen (N) and phosphorus (P) concentration.

Effect	*df*†	N		P	
		Straw	Grain	Straw	Grain
		---2016---			
site location	3	**< 0.0001**‡	**< 0.0001**	**< 0.0001**	**< 0.0001**
fertilizer treatment	1	0.2094	0.8504	**0.0112**	**< 0.0001**
site location*fertilizer treatment	3	0.6668	0.7998	0.2338	0.1428
cultivar	3	**0.0105**	**< 0.0001**	0.4625	**< 0.0001**
site location*cultivar	9	**0.0049**	**0.0041**	0.1615	**0.0013**
fertilizer treatment*cultivar	3	0.6185	0.1185	0.6727	**0.0399**
site location*fertilizer treatment*cultivar	9	0.5132	0.4936	0.8529	0.1800
		---2017---			
site location	2	**<0.0001**	0.0789	**0.0002**	**0.0007**
fertilizer treatment	1	0.5660	0.4929	0.6864	0.0753
site location*fertilizer treatment	2	0.4070	0.1164	0.3979	**0.0477**
cultivar	3	0.0841	**0.0013**	0.0913	**0.0035**
site location*cultivar	6	0.8721	**0.0157**	0.1073	**0.0041**
fertilizer treatment*cultivar	3	0.4436	0.7035	0.4821	0.0539
site location*fertilizer treatment*cultivar	6	0.7223	0.3629	0.6635	0.2591

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Site location, fertilizer treatment and cultivar had significant effects on faba bean N and P concentration (Table 3.7). Site location had a significant impact on N and P concentrations in both years, with greater concentrations of N and P in faba bean straw at Outlook in 2016, reflective of low yield, and at Saskatoon in 2017 (Table 3.8). Faba bean grain N and P concentrations at Saskatoon were greater than the other sites in 2016 and the highest faba bean grain P concentrations were found at Saskatoon and Meath Park in 2017. Cultivars with the greatest faba bean grain N and P concentrations varied among site locations, but Snowbird grain N concentrations were generally less than grain concentrations of other cultivars in 2016 and 2017 (Table 3.9). Fertilization generally did not affect N concentration in either year or P concentration in 2017, but both straw and grain P concentrations were increased when fertilizer was applied in the 2016 field study. Cultivar influenced straw N concentrations in 2016 and grain N and P concentrations in 2016 and 2017. Cultivar 219-16 had higher straw N concentration than other cultivars in 2016 and Snowbird generally had lower grain N and P concentration than the other cultivars in 2016, and at two of the three site locations in 2017 (Table 3.8).

Table 3.8. Straw and grain nitrogen (N) and phosphorus (P) concentration (n=4) of four faba bean cultivars at the four 2016 and the three 2017 field site locations.

Site Location	Cultivar	2016				2017			
		N		P		N		P	
		Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
		g kg^{-1}							
Meath Park	CDC Snowdrop	2.9 a†	39.7 a	0.6 a	5.6 a	3.5 a	39.6 a	0.2 a	4.4a
	219-16	3.4 a	38.5ab	0.3 a	5.2 b	3.6 a	39.8 a	0.3 a	4.7a
	Snowbird	3.0 a	35.5 b	0.5 a	5.1 b	3.4 a	39.9 a	0.2 a	4.7a
	Tabasco	3.5 a	39.3 a	0.4 a	5.0 b	3.6 a	39.3 a	0.3 a	4.6a
Rosthern	CDC Snowdrop	3.2bc	39.4ab	0.2 b	4.2ab	3.6 a	42.2 a	0.2 a	3.9a
	219-16	3.4ab	40.6 a	0.2ab	4.1 b	3.8 a	42.1 a	0.2 a	3.8a
	Snowbird	3.7 a	38.8 b	0.3 a	3.8 c	3.4 a	39.8 b	0.2 a	3.5b
	Tabasco	2.9 c	41.1 a	0.2 b	4.5 a	3.8 a	41.2 a	0.2 a	3.8a
Saskatoon	CDC Snowdrop	3.3ab	40.6 b	0.3ab	5.7 b	4.5ab	40.4ab	0.4ab	4.6b
	219-16	3.8 a	42.3 a	0.3ab	5.6 b	4.4ab	41.6 a	0.3 b	4.7b
	Snowbird	3.1 b	40.5 b	0.2 b	5.2 c	4.2 b	39.0 b	0.4ab	4.4b
	Tabasco	3.7 a	42.0 a	0.4 a	6.1 a	4.9 a	41.6 a	0.5 a	5.4a
Outlook	CDC Snowdrop	5.1 b	40.6 a	0.8 a	5.5 a	-‡	-	-	-
	219-16	6.3 a	39.8 a	0.8 a	5.2ab	-	-	-	-
	Snowbird	4.5 b	38.0 b	0.7 a	4.9 b	-	-	-	-
	Tabasco	4.7 b	38.5 b	0.7 a	5.2ab	-	-	-	-

† Within a column, means within a site location followed by the same letter are not significantly different from each other ($p \geq 0.05$).

‡ The 2017 Outlook site location faba bean crop was destroyed by hail. Data not available.

Total Average N uptake by faba bean was 230 kg N ha^{-1} in 2016 and 2017 and total average P uptake by faba bean was 29 kg P ha^{-1} in 2016 and 24 kg P ha^{-1} in 2017, with the majority of aboveground N and P uptake found in the faba bean grain in both field study years as revealed in the uptake harvest index (Tables 3.9 and 3.10). Saskatoon generally had the greatest N and P uptakes in 2016 and 2017, but the interaction between site location and cultivar was significant for grain N and grain and straw P uptake and the interaction between the three factors was significant for straw N uptake in 2016 (Table 3.9). In both 2016 and 2017, fertilization increased straw N uptake and in 2016, straw and grain P uptake were increased by fertilization (Table 3.9), but the increase in uptake when fertilizer was applied was small. Straw N uptake and grain P uptake by the Snowbird cultivar were less than uptakes by the other cultivars in 2017.

Table 3.9. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 faba bean field trial nitrogen (N) and phosphorus (P) uptake, nitrogen harvest index (NHI) and phosphorus harvest index (PHI). Harvest index = grain uptake/grain+straw uptake.

Effect	***df*†**	**N**		**P**		**NHI**	**PHI**
		Straw	**Grain**	**Straw**	**Grain**		
	2016						
site location	3	**0.0004**‡	**0.0008**	**< 0.0001**	**< 0.0001**	**<0.0001**	**<0.0001**
fertilizer treatment	1	**0.0161**	0.0708	**< 0.0001**	**0.0040**	0.0899	**0.0079**
site location*fertilizer treatment	3	0.2952	0.5742	0.2043	0.1295	0.6371	0.2223
cultivar	3	**0.0011**	0.9135	**0.0050**	0.5410	**0.0011**	0.2018
site location*cultivar	9	0.1460	**0.0152**	**0.0019**	**0.0202**	**0.0005**	0.1121
fertilizer treatment*cultivar	3	0.3347	0.8136	0.8426	0.8494	0.5329	0.5124
site location*fertilizer treatment*cultivar	9	**0.0216**	0.1489	0.1298	0.1665	0.3146	0.8218
	2017						
site location	2	**0.0002**	**0.0031**	**<0.0001**	**0.0012**	**0.0034**	**0.0008**
fertilizer treatment	1	**0.0199**	0.1083	0.0833	0.3769	0.9183	0.8166
site location*fertilizer treatment	2	0.7683	0.9741	0.0523	0.2420	0.7040	0.6476
cultivar	3	**0.0348**	0.2128	0.0847	**0.0479**	0.4998	0.5498
site location*cultivar	6	0.1868	0.2452	0.1504	0.0968	**0.0063**	0.0507
fertilizer treatment*cultivar	3	0.4342	0.8405	0.1454	0.7153	0.3102	0.6323
site location*fertilizer treatment*cultivar	6	0.5913	0.7889	0.3025	0.6981	0.2989	0.8632

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference (p≥0.05).

Table 3.10. Mean straw and grain nitrogen (N) and phosphorus (P) uptake (kg ha^{-1}), N harvest index (NHI) and P harvest index (PHI) (n=4) of four faba bean cultivars at four 2016 and three 2017 field study site locations. Harvest index = grain uptake/grain+straw uptake. Values are means of fertilized and unfertilized treatments.

Site location	Cultivar	N		P		NHI	PHI
		Straw	Grain	Straw	Grain		
		kg ha^{-1}				%	
		----------2016----------					
Meath Park	CDC Snowdrop	14 a†	228 a	2.4 a	32 a	94 a	92 a
	219-16	13 a	221 a	1.3 b	30 a	94 a	95 a
	Snowbird	11 a	195 a	1.6ab	28 a	95 a	94 a
	Tabasco	22 a	222 a	0.9 b	28 a	92 a	94 a
Rosthern	CDC Snowdrop	17 a	254ab	1.1 a	27bc	93 b	96 a
	219-16	17 a	288 a	1.1 a	29ab	94 a	96 a
	Snowbird	16 a	242 b	1.1 a	24 c	94ab	95 a
	Tabasco	18 a	290 a	1.2 a	32 a	94ab	96 a
Saskatoon	CDC Snowdrop	25ab	241 b	2.3ab	34 a	91 b	94ab
	219-16	24 b	220 b	2.0 b	29 b	90bc	94ab
	Snowbird	22 b	271 a	1.7 b	35 a	92 a	95 a
	Tabasco	29 a	234 b	2.9 a	34 a	89 c	92 b
Outlook‡	CDC Snowdrop	20ab	128 a	3.2 a	17 a	86ab	84 a
	219-16	23 a	122 a	2.8ab	16 a	84 b	85 a
	Snowbird	14 c	120 a	1.8 b	15 a	89 a	88 a
	Tabasco	18bc	117 a	2.6ab	16 a	85 b	85 a
		----------2017----------					
Meath Park	CDC Snowdrop	15 a	190 a	1.0 a	21 a	92 a	95 a
	219-16	18 a	174 a	1.2 a	20 a	91 c	94 a
	Snowbird	14 a	163 a	1.0 a	19 a	92ab	95 a
	Tabasco	14 a	155 a	1.1 a	18 a	91bc	94 a
Rosthern	CDC Snowdrop	16 a	191 a	0.8 a	17 a	92 a	95 a
	219-16	15 a	204 a	1.0 a	18 a	93 a	95 a
	Snowbird	15 a	195 a	0.8 a	17 a	93 a	95 a
	Tabasco	17 a	214 a	1.0 a	20 a	93 a	95 a
Saskatoon	CDC Snowdrop	32 a	253ab	2.8ab	29 b	89 b	91 b
	219-16	29ab	300 a	2.2 c	33ab	91 a	94 a
	Snowbird	23 b	236 b	2.3bc	27 b	90ab	92 b
	Tabasco	31 a	282ab	3.0 a	36 a	90ab	92ab

† Within a column, means within a site location followed by the same letter are not significantly different from each other ($p \geq 0.05$).

‡ The 2017 Outlook site location faba bean crop was destroyed by hail. Data not available.

Average N harvest indices (NHI) and P harvest indices (PHI) were similar for both treatments, all cultivars, at all site locations in both 2016 and 2017, except for at the Outlook site location where both the NHI and PHI were significantly lower (Table 3.10).

3.5.1.2 Fall residual available soil nitrate and phosphorus

In 2016 and 2017, post-harvest soil NO_3 was significantly influenced by site location at all soil depths, as shown in Table 3.11. Field trial plots at the Saskatoon site location had greater NO_3 in the top two (0-15 cm and 15-30 cm) soil depths in both years and greater NO_3 in the 30-60 cm depth at both the Saskatoon and Rosthern site locations in 2017 (data not shown). At Saskatoon, cultivar Snowbird plots generally had higher residual available soil NO_3 than other cultivar plots in both years (Table 3.12).

Table 3.11. Type III fixed effects ANOVA *p* value summary for soil residual nitrate (NO_3) in three soil depths (0-15, 15-30 and 30-60 cm) at the 2016 and 2017 field site locations.

Effect	***df*†**	**0-15 cm**	**15-30 cm**	**30-60 cm**
			NO_3	
			2016	
site location	3	**<0.0001**‡	**<0.0001**	**<0.0001**
fertilizer treatment	1	0.3103	0.4508	0.1284
site location*fertilizer treatment	3	0.2028	0.5249	0.1018
cultivar	3	**0.0003**	0.0680	0.0704
site location*cultivar	9	**0.0073**	0.1051	0.2339
fertilizer treatment*cultivar	3	0.9398	0.4257	0.6045
site location*fertilizer treatment*cultivar	9	0.1725	0.1932	0.9129
			2017	
site location	2	**<0.0001**	**0.0006**	**<0.0001**
fertilizer treatment	1	0.8959	0.3255	0.0733
site location*fertilizer treatment	2	0.4879	0.2357	0.2678
cultivar	3	0.3427	0.2461	0.3168
site location*cultivar	6	0.2400	0.6030	0.5936
fertilizer treatment*cultivar	3	0.9895	0.9736	0.5544
site location*fertilizer treatment*cultivar	6	0.8183	0.4585	0.2585

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 3.12. Mean soil residual available nitrate (NO_3) (n=4) in the 0-15 cm soil depth of four faba bean cultivars at the four 2016 and three 2017 field site locations after harvest. Values are means of fertilized and unfertilized treatments.

Site location	Cultivar	2016	2017
		NO_3	
		kg ha^{-1}	
Meath Park	CDC Snowdrop	4.4 a†	8.0 a
	219-16	4.8 a	6.9 a
	Snowbird	5.8 a	5.9 a
	Tabasco	5.0 a	6.9 a
Rosthern	CDC Snowdrop	15.4 a	2.7 a
	219-16	16.2 a	2.0 a
	Snowbird	17.1 a	2.9 a
	Tabasco	10.2 b	2.7 a
Saskatoon	CDC Snowdrop	11.3 c	8.6 b
	219-16	15.9 a	15.4 a
	Snowbird	14.6ab	11.2ab
	Tabasco	11.7bc	7.4 b
Outlook	CDC Snowdrop	7.0 a	-‡
	219-16	7.4 a	-
	Snowbird	6.6 a	-
	Tabasco	6.9 a	-

† Within a column, means within a site location followed by the same letter are not significantly different from each other (p≥0.05).

‡ The 2017 Outlook site location faba bean crop was destroyed by hail. Data not available.

Site location also affected available soil P measured in the fall after harvest at the 0-15 cm soil depth in 2016 and 2017, with the Saskatoon site location having greater available P and the Outlook site having less available P in the 2016 field study trials (data not shown). Fertilization increased available P in the 0-15 cm soil depth in 2016 and 2017 and although cultivar had no significant effect on post-harvest soil available P in the 0-15 cm soil depth in either field study year, the interaction between fertilization and cultivar was significant for available P in 2017 (Tables 3.13 and 3.14). Available P in the 0-15 cm soil depth was greater after fertilization for all cultivars in 2016, but cultivar 219-16 was the only cultivar that had greater available soil P after fertilization in 2017 (Table 3.14).

Table 3.13. Type III fixed effects ANOVA *p* value summary for fall modified Kelowna extractable soil phosphorus (P) in the 0-15 cm soil depth at the 2016 and 2017 field site locations.

Effect	*df*†	P
	-------***2016***-------	
site location	3	**0.0333**‡
fertilizer treatment	1	**<0.0001**
site location*fertilizer treatment	3	0.3652
cultivar	3	0.9972
site location*cultivar	9	0.0536
fertilizer treatment*cultivar	3	0.8719
site location*fertilizer treatment*cultivar	9	0.2990
	-------***2017***-------	
site location	2	**0.0025**
fertilizer treatment	1	**0.0467**
site location*fertilizer treatment	2	0.0736
cultivar	3	0.6189
site location*cultivar	6	0.4886
fertilizer treatment*cultivar	3	**0.0481**
site location*fertilizer treatment*cultivar	6	0.6647

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference (p≥0.05).

Table 3.14. Mean modified Kelowna extractable soil phosphorus (P) (n=4) in the 0-15 cm soil depth of two fertilizer treatments for four faba bean cultivars at four 2016 and three 2017 site locations in fall after harvest.

Cultivar	Fertilizer treatment	2016	2017
		P	
		kg ha^{-1}	
CDC Snowdrop	Unfertilized	36.2b†	32.7a
	Fertilized	45.3a	42.7a
219-16	Unfertilized	33.9b	32.5b
	Fertilized	46.8a	49.3a
Snowbird	Unfertilized	34.8b	39.7a
	Fertilized	45.8a	41.4a
Tabasco	Unfertilized	35.2b	36.7a
	Fertilized	45.6a	40.4a

† Within a column, means within a cultivar followed by the same letter are not significantly different from each other (p≥0.05).

3.5.2 Glasshouse faba bean phosphorus fertilization response study

3.5.2.1 Faba bean biomass yield, nitrogen fixation, nitrogen and phosphorus concentration and uptake, residual available soil nitrate and phosphorus

In the glasshouse pot experiment, biomass yield of the two faba bean cultivars responded positively to P fertilization (p = 0.064) (Tables 3.15 and 3.16), reflecting the low available P content of the soil of 6 mg MK extractable P kg^{-1} (Table 3.5). Overall, the average %Ndfa by faba bean was 88% and, depending on faba bean cultivar or rate of fertilizer treatment applied, the mean %Ndfa by faba bean ranged from 81 to 93%. Yield, %Ndfa, and the amount of Ndfa was greater for cultivar CDC Snowdrop than for Snowbird (Table 3.16).

Table 3.15. Type III fixed effects ANOVA *p* value summary for aboveground biomass and nitrogen (N) yield, proportion (%) of N, and biological nitrogen fixation (BNF) components (%Ndfa, Ndfa, Ndff, Ndfs) in 2017 glasshouse study.

Effect	*df* †	Yield	N Yield	%N	%Ndfa‡	Ndfa‡	Ndff‡	Ndfs‡
cultivar	1	**0.0393**§	**0.0316**	0.1787	**0.0360**	**0.0339**	0.2313	0.3559
fert trt‡	2	0.0635	0.1251	0.0977	0.0779	0.1012	**0.0306**	0.3003
cultivar*fert trt	2	0.9458	0.9713	0.3035	0.5472	0.9644	0.3210	0.4148

† *df* = numerator degrees of freedom.

‡ %Ndfa = proportion (%) of nitrogen derived from atmosphere; Ndfa = nitrogen derived from atmosphere; Ndff = nitrogen derived from fertilizer; Ndfs = nitrogen derived from soil; fert trt = fertilizer treatment.

§ Bolded values denote significant difference ($p \geq 0.05$).

Table 3.16. Mean aboveground yield and nitrogen (N) components (n=4) of two faba bean cultivars in 2017 glasshouse faba bean P fertilization response study. Values represent mean values of three phosphorus (P) treatments.

Cultivar	Yield	N Yield	N	Ndfa‡	Ndfa‡	Ndff‡	Ndfs‡
	g pot^{-1}	mg pot^{-1}	-------%-------		--------mg pot^{-1}---------		
CDC Snowdrop	9.8a†	221a	2.3a	90a	200a	2.0a	18a
Snowbird	7.4b	158b	2.1a	85b	139b	1.8a	16a

† Within a column, means followed by the same letter are not significantly different from each other ($p \geq 0.05$).

‡ %Ndfa = proportion of nitrogen derived from atmosphere; Ndfa = nitrogen derived from atmosphere; Ndff = nitrogen derived from fertilizer; Ndfs = nitrogen derived from soil.

Faba bean cultivar CDC Snowdrop had greater above- and belowground N and P uptake than Snowbird (Tables 3.17 and 3.18) and less soil residual available NO_3 and P than Snowbird (Tables 3.19 and 3.20). Fertilization with P had no significant effect ($p \geq 0.05$) on %Ndfa but had a significant effect on the amount of Ndff (mg pot^{-1}), aboveground faba bean P uptake and residual available soil P, with greater Ndff, P uptake and soil P as the rate of P fertilizer increased. The only significant interaction in the glasshouse study was between cultivar and fertilizer treatment for residual available soil P, where residual available soil P was greater with higher rates of fertilizer for both cultivars, but the greatest amount of residual available P for Snowbird was greater than the greatest amount for CDC Snowdrop.

Table 3.17. Type III fixed effects ANOVA *p* value summary for the 2017 glasshouse phosphorus (P) fertilization response study faba bean above- and belowground nitrogen (N) and P concentration and uptake.

Effect	***df*†**	**Concentration**		**Uptake**	
		N	**P**	**N**	**P**
		-------------------------***Aboveground***		--------------------------	
cultivar	1	0.3007	0.4972	**0.0253**‡	0.0425
fertilizer treatment	2	0.4160	0.3066	0.1624	**0.0003**
cultivar*fertilizer treatment	2	0.5322	0.9921	0.9849	0.7808
		-------------------------***Belowground***		--------------------------	
cultivar	1	0.1927	0.2740	**0.0089**	**0.0172**
fertilizer treatment	2	0.4525	0.9406	0.8145	0.5218
cultivar*fertilizer treatment	2	0.7068	0.3812	0.9418	0.8930

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 3.18. Above- and belowground nitrogen (N) and phosphorus (P) concentration and uptake (n=4) of two faba bean cultivars and three P treatments in the 2017 glasshouse P fertilization response study.

Cultivar	**Concentration**		**Uptake**	
	N	**P**	**N**	**P**
	mg kg^{-1}		**mg pot^{-1}**	
	---------------------------------------***Aboveground***		---	
CDC Snowdrop	20404a†	1833a	199a	18a
Snowbird	18718a	1962a	139b	14b
	---------------------------------------***Belowground***		---	
CDC Snowdrop	17586a	1048a	47a	3a
Snowbird	15219a	977a	33b	2b

† Within a column, means followed by the same letter are not significantly different from each other ($p \geq 0.05$).

Table 3.19. Type III fixed effects ANOVA *p* value summary for 2017 glasshouse study soil pH, electrical conductivity (EC) and available nitrate (NO_3) and modified Kelowna extractable phosphorus (P).

Effect	*df*†	pH	EC	NO_3	P
cultivar	1	**0.0347**‡	0.8505	**0.0478**	**0.0154**
fertilizer treatment	2	0.8982	0.6810	0.5249	**<0.0001**
cultivar*fertilizer treatment	2	0.4848	0.1948	0.6838	**0.0290**

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference (p≥0.05).

Table 3.20. Soil pH, electrical conductivity (EC) and residual available nitrate (NO_3) and modified Kelowna extractable phosphorus (P) (n=4) of two faba bean cultivars and three P treatments in the 2017 glasshouse faba bean P fertilization response study.

Cultivar	Fertilizer treatment	pH	EC	NO_3	P
	mg P pot^{-1}		dS m^{-1}	mg pot^{-1}	
CDC Snowdrop	0	7.6ab†	0.48a	13.57a	15.11 d
	60	7.6ab	0.50a	15.30a	35.15 c
	120	7.6 a	0.48a	12.47a	43.92 b
Snowbird	0	7.5ab	0.48a	26.91a	17.54 d
	60	7.5ab	0.47a	23.08a	35.75bc
	120	7.5 b	0.52a	17.18a	60.97 a

† Within a column, means followed by the same letter are not significantly different from each other (p≥0.05).

3.6 Discussion

3.6.1 Faba bean yield

3.6.1.1 Field study faba bean grain and straw yields

In the current study, the overall average faba bean yields of both fertilizer treatments from the four sites in 2016 and the three site locations in 2017 were considerably higher than in a Swift Current study, with straw yields of 5,206 kg ha^{-1} in 2016 and 5,028 kg ha^{-1} in 2017, and grain yields of 5,323 kg ha^{-1} in 2016 and 5,242 kg ha^{-1} in 2017. In the study conducted near Swift Current, Saskatchewan in 2008 - 2010, Hossain et al. (2017) reported that the average faba bean straw yield was 2,015 kg ha^{-1} (2008), 2,032 kg ha^{-1} (2009) and 4,634 kg ha^{-1} (2010), and grain yield was 886 kg ha^{-1} (2008), 1,948 kg ha^{-1} (2009) and 3,009 kg ha^{-1} (2010). It is important to note that the yields in this study were determined by hand harvesting, which could result in lower losses and higher yields than harvest of the same site with a combine harvester. Overall, faba bean grain yield at the sites in 2016 and 2017 tended to be similar to, or slightly higher, than straw yield, with a higher harvest index than in the Swift Current study. Though the effect of growing year on grain yield was highly significant in the Swift Current study (Hossain et al., 2017), faba bean straw yield relative to grain yield was quite consistent in all three years. In contrast, the proportion of straw yield to grain yield in the current study differed based on the year of study and the site location. Lower harvest index at Saskatoon and Outlook site locations that were nearest to the Swift Current study of Hossain et al. (2017) may reflect drier summer conditions at the Saskatoon site as well as injury from sand blasting of the faba beans at the Outlook site in 2016.

Average yields for the four cultivars in 2016 and 2017 at the Rosthern and Saskatoon sites in this study were similar to average combine harvester yields for 15 faba bean cultivars at Rosthern and Saskatoon sites in a study reported on by Bueckert et al. (2011) in 2009. Average yields at Rosthern in 2009 ranged from 4,990 to 6,170 kg ha^{-1} (Bueckert et al., 2011), while they ranged from 2,414 to 8,304 kg ha^{-1} in 2016 and 2017 in this study. At Saskatoon, average yields ranged from 4,470 to 6,500 kg ha^{-1} in 2009 (Bueckert et al., 2011), and from 3,571 to 9,757 kg ha^{-1} in 2016 and 2017 in this study. Harvest indices ranged from 34 to 45% in 2009 (Bueckert et al., 2011) and in this study from 36 to 63% in 2016 and 42 to 60% in 2017. Bueckert et al. (2011) found the Snowbird cultivar had the highest yield at Rosthern and Saskatoon locations in 2009. Conversely, this study found that Snowbird had the lowest mean total (grain+ straw) yield in 2016 and 2017 and the lowest average grain yield in 2017, but the greatest grain yield of all the cultivars in 2016.

The unfertilized grain yield in this study that ranged from 3,099 to 6,481 kg ha^{-1} in 2016 and 2017 was much greater than average grain yield at physiological maturity in a two-year unfertilized faba bean field study in Massachusetts, USA, that ranged from 803 to 2,618 kg ha^{-1} (Etemadi et al., 2018). This suggests that soil and environmental factors can have a profound influence on the faba bean yield components, along with cultivar.

3.6.1.2 Glasshouse phosphorus fertilization response study faba bean biomass yield

The glasshouse P fertilization response study most comparable to the glasshouse study conducted in this thesis work was reported on by Bolland et al. (1999), who examined the response of grain legumes, wheat and canola to applications of single superphosphate in a glasshouse study in south-western Australia (WA). The plants were harvested 42 d after sowing, so yield, N and P concentration and uptake measurements cannot be directly compared to yield and nutrient components of faba bean in the current glasshouse study, but the results of the study in Australia give cause for further consideration of yield results from the current study. In the study by Bolland et al. (1999), faba bean, albus lupin and chickpea produced greater aboveground biomass when no P fertilizer was applied, with less response to added P than wheat and canola. It was suggested that these results were due to the greater seed size and seed P content of the grain legumes compared to wheat and canola that supplied P early on to the germinating seed and seedling. Another explanation lies in the greater ability of legumes to scavenge P from the soil compared to other crops. Legumes are reported to possess a considerable capability to mobilize sparingly soluble P from soils (Wang et al., 2012) compared to less P efficient cereal crops.

In Saskatchewan, Henry et al. (1995) conducted a P fertilizer placement and response study at three field locations and found that when compared with pea and lentil, faba bean seed yield was the most responsive to P fertilization and was the most tolerant to seed-placed P (SPG, 2018). The response of faba bean to P fertilizer was especially noticeable under irrigated field conditions. Interestingly, the results of the current study showed that when two faba bean cultivars were compared, the cultivar with a smaller seed size (CDC Snowdrop) had a significantly greater yield, %Ndfa, Ndfa (mg pot^{-1}), and above- and belowground N and P uptake. However, yield and %Ndfa of Snowbird tended to respond more to P fertilization. Unfortunately, in the current study we did not measure the P concentration in the seeds that were planted. It would be useful to conduct further investigation into how different grain legume species or different grain legume cultivars from the same species with different seed sizes and documented seed P contents respond to P fertilization.

3.6.2 Faba bean nitrogen and phosphorus uptake

3.6.2.1 Field study faba bean nitrogen uptake

When compared to faba bean N uptake in other Saskatchewan field studies, faba bean straw N uptake in this study was less than the faba bean straw N uptake reported for the 2009 field study by Bueckert et al. (2011) at Rosthern and Saskatoon and in the 2008, 2009 and 2010 field studies by Hossain et al. (2018) in Swift Current. Bueckert et al. (2011) found that vegetative biomass N uptake was considerably higher and ranged from 100 to 150 kg N ha^{-1} at the field sites in 2009 while Hossain et al. (2018) found that average straw N uptake ranged from 31 to 73 kg N ha^{-1} in the three years of their study. This is compared to N uptake by faba bean straw in this study that ranged from 11 to 32 kg N ha^{-1} in 2016 and 2017. However, when comparing faba bean grain N uptake among studies, Bueckert et al. (2011) and the current study had similar grain N uptake, while grain N uptake was less in the study by Hossain et al. (2018). In the 2009 season in the study by Bueckert et al. (2011), grain N uptake by faba bean ranged from 200 to 350 kg N ha^{-1} and was similar to the grain N uptake that ranged from 117 to 300 kg N ha^{-1} in this study, whereas average grain N uptake found by Hossain et al. (2018) was 39 to 116 kg N ha^{-1}. The importance of measuring N and P uptake of multiple faba bean cultivars at multiple site locations to provide a meaningful range was evident in the effect of site location on most N and P uptake components and in the significant interactions found between factors of these components in this study.

3.6.2.2 Glasshouse study faba bean nitrogen uptake

In a faba bean N fertilization response experiment conducted in a glasshouse by Rose et al. (2016) in New South Wales (NSW), Australia, it was discovered that faba bean shoot N content was greater when 0 kg N ha^{-1} fertilizer was added than when 50 kg N ha^{-1} of fertilizer was added. It was observed that mean shoot N uptake increased with increasing P fertilizer rates in the current study, although the N uptakes were not significantly different at $p< 0.05$. In the study by Rose et al. (2016), average faba bean shoot N content was 237 mg plant^{-1} when 0 N fertilizer was applied and was 196, 258 and 287 mg plant^{-1} at applied N fertilizer rates of 50, 100 and 150 kg N ha^{-1}, respectively. Similarly, shoot N uptake was 138 mg pot^{-1} (equivalent to 69 mg plant^{-1}) when 0 P fertilizer was added and was 138, 172 and 198 mg pot^{-1} (equivalent to 69, 86 and 99 mg plant^{-1}) at applied P fertilizer rates of 0, 60 and 120 mg P pot^{-1}, respectively, in the current glasshouse study. It can be noted that two faba bean plants were grown per pot. Stimulation of growth and BNF through fertilization with P in this thesis study may explain the trend towards greater N in the biomass of P fertilized faba bean.

Due to differences in the two glasshouse studies, such as faba bean being harvested at the beginning of flowering in the study by Rose et al. (2016) compared to maturity in the current study, the N uptake values cannot be directly compared, but it was interesting to observe how different rates of added N and added P affected the faba bean shoot N content/uptake differently. Though shoot N content/uptake was highest for the two highest rates of added N and P in the two studies, shoot N content was not the least when 0 kg N ha^{-1} of N fertilizer was applied, whereas shoot N uptake was the least when 0 mg P pot^{-1} of P fertilizer was applied. This is likely due to the ability of faba bean to fix N_2 when available soil NO_3 does not satisfy the amount of N uptake required by the plant.

3.6.2.3 Field study and glasshouse study faba bean phosphorus uptake

Information on nutrient uptake by faba bean for nutrients other than N is limited in other field and glasshouse studies. The grain P uptake and removal by faba bean in the current field study ranged from about 15 to 35 kg P ha^{-1} (34 to 80 kg P_2O_5 ha^{-1}) and was similar to the 27 to 33 kg P ha^{-1} (62 to 75 kg P_2O_5 ha^{-1}) reported to be removed by faba bean grain in the field, according to the Canadian Fertilizer Institute (2001) and Saskatchewan Pulse Growers (SPG; 2018), for a 3,800 kg ha^{-1} faba bean yield, which falls within the range of the current study. Nearly all P was in faba bean grain for all cultivars in 2016 and 2017. At the rate of P removed through uptake by faba bean grain at harvest in this study, faba bean would relatively rapidly deplete soil P reserves over time if no P is added back into the system.

3.6.2.4 Faba bean nitrogen and phosphorus uptake compared to other pulses

Compared to N and P uptake by pulses in other Saskatchewan field studies, faba bean N and P uptake in the straw component in the current study was less while grain N and P uptake was greater, and overall N and P uptake was greater. This suggests that N and P requirements are greater for modern faba bean cultivars used in this study than for pulses assessed in other Saskatchewan studies.

Hossain et al. (2018) conducted a field study in Swift Current that compared N uptake by faba bean with N uptake by other pulses and even though field pea straw yield was greater than faba bean straw yield (Hossain et al., 2017), faba bean had the greatest average straw N uptake (47.1 kg N ha^{-1}), followed by chickpea (41.9 kg N ha^{-1}), lentil (41.2 kg N ha^{-1}), field pea (39.8 kg N ha^{-1}) and dry bean (11.7 kg N ha^{-1}) (Hossain et al., 2018). However, average faba bean straw N uptake in the current field study was 19 kg N ha^{-1}; less than all pulses in the field study by Hossain et al. (2018). Conversely, the highest average grain N uptakes by faba bean (78.8 kg ha^{-1}) and by field pea (80.9 kg ha^{-1}) from the Swift Current study were less than the average faba bean grain N uptake (212 kg N ha^{-1}) from this study. Grain N uptake by lentil (70.4 kg N ha^{-1}), chickpea (51.2 kg N ha^{-1}) and dry bean (37.2 kg N ha^{-1}) were even less (Hossain et al., 2018).

The N and P uptake by faba bean in this study cannot be directly compared to another pulse crop nutrient uptake study conducted by Xie et al. (2018) in 2014 because the current field study was conducted three years later and not all of the sites were the same. However, the study by Xie et al. (2018) is useful in providing N and P uptake for other legumes (soybean, pea, lentil) grown in similar site locations under similar field conditions for general comparison. In the 2014 Saskatchewan pulse field study by Xie et al. (2018), straw N uptake ranged from 18.0 to 57.9 kg N ha^{-1} for soybean, 43.0 to 104.1 kg N ha^{-1} for pea, and 20.5 to 93.0 kg N ha^{-1} for lentil, and straw P uptake ranged from 3.1 to 8.8 kg P ha^{-1} for soybean, 3.1 to 10.2 kg P ha^{-1} for pea, and 2.0 to 11.8 kg P ha^{-1} for lentil., In the current field study, straw N and P uptake by faba bean ranged from 11 to 32 kg N ha^{-1} in 2016 and 0.8 to 3.2 kg P ha^{-1} in 2017, and were considerably lower than N and P uptake reported for the other pulses in 2014. Grain N uptake ranged from 40.4 to 168.0 kg N ha^{-1} for soybean, 33.7 to 186.9 kg N ha^{-1} for pea, and 19.1 to 90.1 kg N ha^{-1} for lentil, in the 2014 study, and grain P uptake ranged from 5.8 to 21.2 kg P ha^{-1} for soybean, 6.1 to 23.1 kg P ha^{-1} for pea, and 2.5 to 10.8 kg P ha^{-1} for lentil (Xie et al., 2018). Contrary to straw N and P uptake by faba bean in this study, grain N uptake ranged from 117 to 300 kg N ha^{-1} and grain P uptake ranged from 15 to 36 kg P ha^{-1}, and were considerably higher than grain N and P uptake by the other pulses grown in 2014. From these comparisons it is evident that faba bean in this study had less straw N and P uptake and greater grain N and P uptake than the other pulses in the field study by Xie et al. (2018) which were conducted at similar site locations under similar field conditions. Based on the results of both Saskatchewan field studies, it can be determined that N and P grain uptake by faba bean is greater than N and P grain uptake by other pulses.

Greater straw N uptake in other pulses than in faba bean of this study is supported by results from studies in other countries, such as in a study conducted by Rose et al. (2016) under glasshouse conditions in Australia where shoot N concentration and N uptake were significantly greater in faba bean than in chickpea. In a systematic literature review conducted by Anglade et al. (2015) of various research plot and farm field studies on grain and forage legumes commonly grown across northern Europe, statistically estimated median values for shoot N (kg N ha^{-1}), and were 174 kg N ha^{-1} by faba bean, 132 kg N ha^{-1} by pea and 96 kg N ha^{-1} by lentil.

3.6.3 Nitrogen and phosphorus partitioning in faba bean

Partitioning of a greater amount of N in faba bean grain than in faba bean straw in this study is generally consistent with partitioning of faba bean N in a study by Bueckert et al. (2011) at two locations in Saskatchewan, which found that there were two parts of total N per unit area in faba bean grain and one part in the stover. Similarly, Etemadi et al. (2018) found in a field study in 2015 and 2016 at the University of Massachusetts Amherst research farm in South

Deerfield, Massachusetts, that faba bean N and P concentration were greatest in grain, followed by pod wall and leaf, and it was suggested that N and P were mobilized from other plant parts to the grain during grain-filling in faba bean, similar to in soybean (Bender et al., 2015).

3.6.3.1 Faba bean nitrogen harvest index (NHI) and phosphorus harvest index (PHI)

High N harvest index (NHI) and P harvest index (PHI) values of faba bean in this study further prove that faba bean is efficient in mobilizing N and P to grain, with average NHI ranging from 84 to 95% and average PHI ranging from 84 to 96% in 2016 and 2017. As with yield, N concentration and uptake, NHI in the current study was likely affected by abiotic factors such as soil type and weather conditions, similarly to the effects on NHI found by Hossain et al. (2017). However, the difference in the study by Hossain et al. (2017) and this study is that the proportion of N uptake by faba bean found in grain was greater in a drier year while the current study found that NHI did not greatly differ in the drier year (2017) versus the wetter year (2016). In this study, NHI and PHI were lower in faba bean at Outlook in 2016, which had the highest amount of precipitation during the growing season of all the site locations, but also suffered from sand blast injury. The significant differences in NHI and PHI at each site location in this study likely depend more on soil type or a combination of abiotic factors, rather than on precipitation alone.

When NHI and PHI and uptake data of faba bean in this study were compared with other pulses in a field study by Xie et al. (2018), it was discovered that NHI and PHI of faba bean were greater than NHI and PHI of soybean, pea and lentil and proportions of straw and grain uptake were most similar between faba bean and soybean. Average NHI values ranged from 45 to 89% for soybean, 41 to 77% for pea and 22 to 61% for lentil, and average PHI values ranged from 41 to 86% for soybean, 46 to 86% for pea and 19 to 67% for lentil. Uptake data in both studies showed that most N and P uptake by faba bean and soybean was found in grain, N and P uptake by pea was slightly more in grain but more equally partitioned between straw and grain, and N and P uptake by lentil was nearly equally distributed between straw and grain, as confirmed by NHI and PHI values. However, in the systematic literature survey conducted by Anglade et al. (2015) on studies across northern Europe, the median NHI value for faba bean (74%) was practically the same as the NHI values for lentil and pea, which were both 75%.

3.6.3.2 Aboveground and belowground nitrogen and phosphorus partitioning in faba bean

The NHI data discussed in the previous section is relevant to a glasshouse study conducted in south-western Australia by Herdina and Silsbury (1990) that predicted the proportion of total plant N found in faba bean grain at maturity would be high at 80%, compared to only 60% of N in pea found in grain, and the proportion of total plant N found in faba bean and pea root would be 6-8%, based on proportions found in faba bean and pea grown in the glasshouse study. Similarly, a review by Jensen at al. (2010) noted that in a 1985 field study in Denmark, N and P grain concentration and overall nutrient requirements were generally greater for faba bean than for pea, but N and P concentrations in empty pods and roots were lower in faba bean than in pea.

Interestingly, the meta-analysis by Walley et al. (2007) used results of Bremer (1991) in which root N of all pulses contributes 14% of total N in the biomass. In the systematic literature survey by Anglade et al. (2015), it was estimated that N derived from faba bean roots, nodules and rhizodeposition, or total belowground plant derived N, contributed 13% of total plant derived N. Although rhizodeposition was not considered in the meta-analysis by Walley et al. (2007) or the belowground nutrient measurements of the current glasshouse study, the estimated proportions of BGN for all pulse crops and for faba bean by Anglade et al. (2015) were the closest to the proportions of BGN in this study, which ranged from 17% to 24% of N uptake^{-1}. Similarly, %BGP in this study ranged from 10 to 20% P uptake^{-1}, and both %BGN and %BGP decreased with increasing P fertilizer treatment rate, as shown in Table 3.21.

Table 3.21. Belowground nitrogen (BGN) uptake as a proportion of total plant nitrogen (N) uptake and belowground phosphorus (BGP) uptake as a proportion of total plant phosphorus (P) uptake (n=4) for two faba bean cultivars with three fertilizer treatments in the 2017 glasshouse phosphorus response study.

Cultivar	**Fertilizer treatment**	**BGN**	**BGP**
	mg P pot^{-1}	**% N uptake^{-1}**	**% P uptake^{-1}**
CDC Snowdrop	0	22 a†	17ab
	60	21ab	14bc
	120	17 b	12 c
Snowbird	0	24 a	20 a
	60	20ab	13bc
	120	18ab	10 c

† Within a column, means followed by the same letter are not significantly different from each other ($p \geq 0.05$).

3.6.4 Biological nitrogen fixation by faba bean compared to other pulses

Assuming 88 %Ndfa by faba bean, based on the average %Ndfa by faba bean observed in fertilized faba beans in the glasshouse study and an average N uptake of 230 kg N ha^{-1} of faba bean in 2016 and 2017 field studies, this equates to an estimation of about 200 kg N ha^{-1} that is potentially contributed to the field system from BNF each year. However, it should be considered that this is only an approximation using an assumed value of %Ndfa based on glasshouse conditions and that harvesting faba bean grain will remove a similar or greater amount of N from the system each year.

This considered, an assumption of 200 kg N ha^{-1} of N_2 fixed by faba bean in the current field study is greater than N_2 fixed by faba bean and most other pulses reported in other recent Saskatchewan field studies. In the three-year field study conducted by Hossain et al. (2017) at Swift Current, average %Ndfa (68%) and N_2 fixed (68 kg N ha^{-1}) by faba bean were the greatest of the five different pulse species measured: faba bean, chickpea, field pea, lentil and dry bean, and average %Ndfa (26%) and N_2 fixed (9.3 kg N ha^{-1}) by dry bean were the least. Even if %Ndfa by faba bean for the current field study was assumed to be 68%, equal to %Ndfa by faba bean in the field study by Hossain et al. (2017), N_2 fixed by faba bean in this study would be 156 kg N ha^{-1}, and still considerably greater than the N_2 fixed by faba bean in the Swift Current study. In the Saskatchewan pulse study by Xie et al. (2018) in 2014, aboveground (straw + grain) N derived from N_2 fixation by soybean was 158 kg ha^{-1}, by pea was 188 kg $ha^{-1}$and by lentil was 133 kg ha^{-1}, and aboveground (straw + grain) %Ndfa by soybean was 70%, by pea was 62%, and by lentil was 62%. Both the N_2 fixed (200 kg N ha^{-1}) and the %Ndfa (88%) by faba bean in the current study were greater than the N_2 fixed and the %Ndfa by soybean, pea and lentil in the 2014 study.

Comparing the %Ndfa by faba bean in this thesis work with other pulses in the Northern Great Plains based on the meta-analysis conducted by Walley et al. (2007) and %Ndfa and N_2 fixed by faba bean and other pulses in the systematic literature survey conducted by Anglade et al. (2015) from studies in northern Europe, the assumed %Ndfa and N_2 fixed by faba bean in the current field study were greater than the other pulses in both studies. Walley et al. (2007) estimated that the faba bean crops researched (n=10) required 65.3 %Ndfa to achieve a positive N contribution to the cropping system, which they all achieved, and that the median levels of %Ndfa by faba bean estimated by Walley et al. (2007) were highest at 88 %Ndfa. Compared to an assumed median value of 89 %Ndfa by faba bean for the current field study, the %Ndfa by faba bean in the meta-analysis was only slightly less, and estimated median values of %Ndfa by faba bean from the meta-analysis and the current field study were both considerably greater than estimated median levels of %Ndfa for kabuli chickpea and common bean (less than 45%), desi chickpea and field pea (about 55%) and lentil (about 60%) in the meta-analysis by Walley et al. (2007). Comparison to Anglade et al. (2015) review results indicate that the estimated median values for %Ndfa and N_2 fixed by faba bean in the current field study are greater than the estimated median values for %Ndfa by the three grain legumes: faba bean (75%), pea (71%) and lentil (66%), and the estimated median values for the amount of shoot N_2 fixed (kg N ha^{-1}) by faba bean (139), pea (82%) and lentil (71.5%).

If N removal in grain harvest is more than the amount of N added to the system through BNF, growing the grain legume will still have a negative effect on the soil N balance. Although the amount of N contained in faba bean grain at harvest relative to that left behind in the straw was very high in the current study, according to the results of the glasshouse pot study there should be considerable (~20% of total plant N) N also left behind in the roots. Therefore the % of total plant N removed in grain harvest may more closely approach the % of total plant N derived from BNF, leading to a greater likelihood of producing no net depletion of soil N when the faba beans are grown.

3.6.5 Response of biological nitrogen fixation by faba bean to phosphorus fertilization

The effect of P fertilization on faba bean was assessed in two earlier field studies, roughly 20 years apart, with similar results. The effect of P fertilizer rate and placement were assessed on three pulses: faba bean, pea and lentil, in a three-year field study in Saskatchewan by Henry et al. (1995) and on faba bean in a more recent study conducted in 2015 by the Indian Head Agricultural Research Foundation (IHARF) (SPG, 2018). The results of the two studies showed that P fertilizer placement does not have a large effect on faba bean yield or nutrient concentration, but that P fertilization rate increased grain yield and grain P concentration under certain conditions. Therefore, there was no need to assess fertilizer placement in the glasshouse study conducted, but P fertilization rate was assessed in the current glasshouse study on two of the faba bean cultivars (CDC Snowdrop and Snowbird) assessed in the field study.

Though %Ndfa and Ndfa (mg pot^{-1}) were not significantly affected by rate of P fertilization on either cultivar in the current glasshouse study, there was a trend for P fertilization to increase the yield and %Ndfa of the Snowbird cultivar. However, it is unknown whether the applied PKS fertilizer treatment affected %Ndfa and Ndfa (kg ha^{-1}) values in the current field study. Because it is difficult and sometimes impractical to directly assess BNF and %Ndfa in field studies, these values are often assumed. This considered, it was discovered in the field and glasshouse studies conducted by Rose et al. (2016) that BNF by faba bean was greater in the glasshouse experiment compared to the field experiment when no N fertilizer was applied and that BNF was greater in the field study when rates of 50 kg N ha^{-1} and 100 kg N ha^{-1} of N fertilizer were applied. It was suggested that BNF by faba bean in the field may be decreased due to high mineral N in the soil or moisture stress (Serraj et al., 1999; Rose et al., 2016), and BNF by faba bean in the field may be greater due to increased competition for applied N from other species in the field when N fertilizer was applied at 50 kg N ha^{-1} and 100 kg N ha^{-1} (Rose et al., 2016). These considerations should be made for the current field and glasshouse studies, where different factors not only affect field and glasshouse studies, but also studies conducted at different times of the year or in different years under different conditions, and assumptions of BNF and %Ndfa should be considered and used with caution. Especially considering the significant interactions found between two or more experimental factors for each yield and BNF component, it is important to measure and compare the yield and BNF components for each of these factors separately.

3.7 Conclusion

The field study results from this thesis research show that soil and environment are major controlling factors of faba bean yield and N and P uptake, which varied with site and growing conditions in the 2016 and 2017 seasons. Although faba bean yield was not significantly affected by cultivar, fertilization or site location, yields differed at site locations in 2016 and 2017, and N and P uptake was significantly affected to varying degrees by all three factors in both study years. Similar to other pulses, partitioning among faba bean grain and straw was found to greatly favor grain. High HI and greater partitioning of N and P uptake in faba bean grain suggests that faba bean is efficient in mobilizing yield biomass, N and P to the grain component. This also suggests that faba bean has the potential to deplete soil N and P reserves over time if no N or P are added back into the system after large amounts of N and P are removed in grain-harvest. However, using the %Ndfa of ~ 88% obtained from the glass house trial for soybean N origin, external input from the atmosphere through BNF may largely replace the N that is removed in grain harvest given a nitrogen harvest index of ~ 90%. Although the majority of faba bean N uptake in the current study comes from BNF, and faba bean yield components showed limited response to fertilization, fertility management of crop rotations that include faba bean crops should consider drawdown of P over the long-term. The potential contribution of N and P in faba bean roots should also be considered. In the glasshouse study, approximately 20% of total plant N and 14% of total plant P was in faba bean roots, which remain in the soil after harvest and can potentially be a source of available N and P to future crops.

The glasshouse study results revealed that the smaller seeded cultivar CDC Snowdrop had significantly greater yield, %Ndfa, amount of Ndfa (mg pot^{-1}) and N and P uptake than the larger seeded Snowbird cultivar, and although yield of the two faba bean cultivars responded positively to increasing P fertilization ($p = 0.064$) in a P deficient soil, yield, %Ndfa and amount of Ndfa (mg pot^{-1}) were not significantly affected by increasing fertilizer rate. Based on these results, the difference in BNF and response to P fertilization observed among cultivars deserves further research attention. Overall, the current field study results suggest that all the modern cultivars of faba bean tested had high yield potential and the glasshouse study results suggest a significant external contribution of N from BNF by faba bean (~ 88 %Ndfa), with greater total BNF by faba bean than by most pulses reported in other recent Saskatchewan studies.

4. Uptake and partitioning of potassium, sulfur, calcium, magnesium, zinc, copper and iron by faba bean in Saskatchewan, Canada as affected by cultivar and fertilization

4.1 Preface

In the previous chapter (Chapter 3), faba bean yield, nitrogen (N) and phosphorus (P) content and removal and biological nitrogen fixation (BNF) by faba bean in a two-year field study (2016 and 2017) and a glasshouse study (2017) in south-central Saskatchewan were reported on. This chapter (Chapter 4) addresses faba bean content and removal of the other essential macronutrients including potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), along with the micronutrients: zinc (Zn), copper (Cu) and iron (Fe). The concentration, uptake and partitioning among yield components is presented, and effects of site location, cultivar and fertilizer treatment are considered.

4.2 Abstract

As faba bean (*Vicia faba* L.) production expands in western Canada, information on crop nutrient requirements that includes recent faba bean cultivars is needed. Some data exists for nitrogen (N) and phosphorus (P), but other macro- and micronutrients have rarely been measured in faba bean nutrition studies, especially on the prairies. Information on nutrient uptake and removal is important in fertility planning for growers and also when considering the human and animal nutritional value of the crop. A two-year field study was conducted in 2016 and 2017 in the faba bean growing region of Saskatchewan with four zero tannin faba bean cultivars and two different fertilizer treatments:1) unfertilized, and 2) fertilized with nitrogen (N), phosphorus (P), potassium (K) and sulfur (S). The study was conducted at four site locations in Saskatchewan in the Dark Brown, Black and Dark Grey soil-climatic zones where faba beans are grown. At the different site locations in 2016 and 2017, average faba bean grain K, S, Ca and Mg contents were 9.8, 1.9, 0.9 and 1.2 g kg^{-1}, respectively, and average grain Zn, Cu and Fe contents were 42.6, 7.9 and 62.2 mg kg^{-1}, respectively. Fertilization significantly increased faba bean straw and grain K, S and Fe concentration in 2016, but only grain S concentration in 2017. Faba bean grain K, S, Ca and Mg uptake at different site locations ranged from 33-69 kg K ha^{-1}, 6-14 kg S ha^{-1}, 3-6 kg Ca $ha^{-1}$and 4-9 kg Mg ha^{-1}, in 2016 and 2017. Faba bean grain harvest removed about 50% of the K in the aboveground plant material and much of the S, Zn, Cu and Fe. Though faba bean nutrient concentration and uptake showed limited response to fertilization, drawdown of base cations, S and micronutrients will need to be considered for future crops grown in rotation with faba bean.

4.3 Introduction

Faba bean (*Vicia faba* L.) is an important grain legume that is grown in crop rotations for its atmospheric N (N_2) fixation-related and non-N related benefits, such as disease resistance to *Aphanomyces euteiches*. Faba bean is consumed by both humans and animals, generally in the form of protein-rich grain (Jensen et al., 2010; Pötzsch et al., 2018). Measurements of faba bean yield, nitrogen (N) and phosphorus (P) concentration and uptake and biological nitrogen fixation (BNF), as discussed in Chapter 3 of this thesis, enable the effects of faba bean on soil N and P fertility, the two most often limiting macronutrients, in a cropping system to be evaluated (Anglade et al., 2015; Li et al., 2010). However, if macronutrients such as potassium (K), sulfur (S), calcium (Ca) and magnesium (Mg), and micronutrients like zinc (Zn), copper (Cu) and iron (Fe), are not available to plants in sufficient quantities, crop growth and quality will suffer. Humans and animals can also be negatively affected by mineral deficiencies in the grains they consume, most commonly micronutrient (Zn and Fe) deficiencies, but Ca and Mg deficiencies can also occur (Etemadi et al., 2018). Global studies have characterized the mineral content of several faba bean cultivars with the purpose of contributing to the improvement of feed nutrition (Makkar et al., 1997) and more sustainable food consumption (Etemadi et al., 2018). Other studies have evaluated the effects of S fertilization on faba bean grain nutrient concentration (Cazzato et al., 2012) and uptake and removal under varying field conditions (Pötzsch et al., 2018), and compared the effects of N fertilization on nutrient requirements of faba bean and pea crops (Jensen et al., unpublished, as reported by Jensen et al., 2010). Unfortunately, concentration, uptake and partitioning of macro- and micronutrients other than N and P are rarely measured and reported in faba bean studies, specifically faba beans grown in western Canada. A previous study that provided this information for pulses in Saskatchewan did not include faba bean in the assessment (Xie et al., 2017).

Therefore, the purpose of the thesis research described in this chapter was to provide new information on concentration, uptake and removal of K, S, Ca, Mg, Zn, Cu and Fe by modern faba bean cultivars grown at contrasting site locations representing different soil-climatic zones in the faba growing region of Saskatchewan. The two-year field study described in Chapter 3 with four zero tannin faba bean cultivars and two fertilizer treatments that was conducted in 2016 and 2017 at four site locations in south-central Saskatchewan, will be further discussed in this chapter in relation to effects of site, cultivar and fertilizer treatment. Assessments made in this component of the study were: (1) measuring yield, concentration and uptake of the macronutrients K, S, Ca and Mg, and micronutrients Zn, Cu and Fe, in faba bean straw and grain, and (2) comparing uptake and crop removal of the macro- and micronutrients by faba bean in the current study to those reported in other studies and with other pulse crops, including soybean, lentil and pea.

4.4 Materials and Methods

4.4.1 Field nutrient uptake trial site descriptions, experimental design and conduct

The nutrient uptake field studies were conducted in 2016 and 2017 at four locations in south-central Saskatchewan: Meath Park, Rosthern, Saskatoon and Outlook, as described previously in Chapter 3 of this thesis. Agronomic practices, soil and plant sampling, analytical methods and statistical data analysis techniques have been covered previously in detail in Chapter 3. For the instrumental measurement of the elements K, Ca, Mg, Cu, Zn and Fe that are covered in this chapter, a description of the instrumental analytical procedures used for elemental analysis is provided.

An Agilent™ Model 200 Atomic Absorption (AA)/Flame Emission (FE) Spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA) was used to measure K, Ca, Mg, Cu, Zn and Fe concentration in soil sample extracts and in the faba bean grain and straw digestions. Sample weights were increased for micronutrient analysis to ensure concentrations were within detection limits on the atomic absorption spectrometer. A LECO S-144DR sulfur analyzer (LECO Corporation, St. Joseph, MI) was used to measure total S concentration in straw and grain samples and an Agilent™ Microwave Induced Plasma Emission Spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA) was used to measure S and B in the soil extracts.

4.5 Results

4.5.1 2016 and 2017 field studies

4.5.1.1 Faba bean potassium, sulfur, calcium, magnesium, zinc, copper and iron concentration and uptake

Overall average aboveground (straw+grain) faba bean macronutrient K, S, Ca and Mg concentrations were 21.2 g K kg^{-1}, 3.0 g S kg^{-1}, 5.5 g Ca $kg^{-1}$and 2.5 g Mg kg^{-1}, with greater K, S and Mg concentrations in faba bean grain in 2016 and greater K, Ca and Mg concentrations in faba bean straw in 2017. Site location influenced faba bean straw and grain K, S, Ca and Mg concentrations in 2016 and, except grain K and Mg concentrations, in 2017 (Table 4.1). Straw and grain K and S were greatest at Saskatoon in both study years. Fertilization with N, P, K and S increased the concentrations of straw and grain K and S in 2016, but only grain S concentration was increased by fertilization in 2017. The interaction between site and fertilizer treatment was significant in 2016 and 2017 (Table 4.1). In 2016, cultivar affected straw Ca and Mg concentration and grain S, Ca, and Mg concentration, with Tabasco having the lowest straw and grain Ca and Mg concentrations and Snowbird having the least grain S concentration, as shown in Table 4.2. In 2017, cultivar also affected straw and grain Mg concentration, with Tabasco having lowest straw and grain Mg concentration overall. The interaction between site and cultivar was significant for grain and straw Mg concentration in 2016 and straw K concentration in 2017 (Table 4.1).

Concentrations of micronutrients Zn, Cu and Fe in the faba bean plant were generally higher in the faba bean grain component in 2016 and 2017, except for a slightly higher straw Fe concentration than grain Fe concentration in 2017. Overall aboveground (straw+grain) average concentrations were 47.9 mg kg^{-1} (Zn), 9.6 mg kg^{-1} (Cu) and 108.1 mg kg^{-1} (Fe). In 2016, site influenced all micronutrient (Zn, Cu and Fe) concentrations except straw Cu and Fe concentration and in 2017, site influenced all straw micronutrient concentrations except straw Cu concentration and all grain micronutrient concentrations except grain Zn concentration (Table 4.3). Fertilization with N, P, K and S significantly increased straw Zn and grain Fe concentrations in 2016 and straw Fe concentration in 2017 and the interaction between site location and fertilizer treatment was significant for straw Zn concentration in 2016 and straw Fe concentration in 2017. Cultivar affected straw and grain micronutrient concentration in 2016, with greater grain Fe concentration in Tabasco than the other faba bean cultivars (Table 4.4). Grain Zn and Cu concentrations were generally greater in CDC Snowdrop than in other faba bean cultivars in 2016, but the interaction between site location and cultivar was significant for grain Zn and Cu concentration (Table 4.3), therefore influencing concentrations of these nutrients in faba bean at different site locations.

It also should be noted that grain Fe concentration was considerably greater in the faba bean cultivars grown in 2017 than in the cultivars grown in 2016 (Table 4.4). This is possibly explained by reduced iron availability to faba bean grown in 2016 due to the wet conditions in that study year, followed by a more typical growing year in 2017 where Fe levels in faba bean returned to more typical levels.

Table 4.1. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial straw and grain potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) concentration.

Effect	*df*†	K	S	Ca	Mg
		---2016---			
		---Straw---			
site location	3	**< 0.0001**‡	**0.0010**	**< 0.0001**	**0.0313**
fertilizer treatment	1	**0.0019**	**< 0.0001**	0.9576	0.3151
site location*fertilizer treatment	3	0.8854	**0.0038**	0.7655	0.4894
cultivar	3	**0.0661**	**0.0469**	**0.0437**	**< 0.0001**
site location*cultivar	9	0.2108	**0.0189**	0.1376	**0.0076**
fertilizer treatment*cultivar	3	0.9930	0.3177	0.8855	0.6476
site location*fertilizer treatment*cultivar	9	0.9065	0.4127	0.2624	0.4390
		---Grain---			
site location	3	**0.0008**	**< 0.0001**	**< 0.0001**	**< 0.0001**
fertilizer treatment	1	**0.0006**	**< 0.0001**	0.9715	0.3169
site location*fertilizer treatment	3	0.0636	**0.0009**	0.5938	0.3889
cultivar	3	0.5799	**0.0120**	**< 0.0001**	**< 0.0001**
site location*cultivar	9	0.0953	0.2476	0.2102	**0.0093**
fertilizer treatment*cultivar	3	0.1401	0.7029	0.5799	0.0725
site location*fertilizer treatment*cultivar	9	0.2705	0.9504	0.2463	0.1285
		---2017---			
		---Straw---			
site location	2	**<0.0001**	**0.0002**	**0.0009**	**<0.0001**
fertilizer treatment	1	0.4233	0.0602	0.8439	0.3502
site location*fertilizer treatment	2	0.0796	**0.0001**	0.8680	0.3933
cultivar	3	0.5568	0.3976	0.5309	**0.0259**
site location*cultivar	6	**0.0337**	0.5117	0.8643	0.0935
fertilizer treatment*cultivar	3	0.5125	0.9985	0.6297	0.5092
site location*fertilizer treatment*cultivar	6	0.5650	0.8743	0.2864	0.7499
		---Grain---			
site location	2	0.2010	**0.0011**	**0.0002**	0.1685
fertilizer treatment	1	0.5637	**0.0347**	0.3222	0.6783
site location*fertilizer treatment	2	0.2185	**0.0063**	0.5623	0.1287
cultivar	3	0.2214	0.1730	0.2406	**0.0003**
site location*cultivar	6	0.6227	0.1494	0.1814	0.4379
fertilizer treatment*cultivar	3	0.1508	0.4062	0.4632	0.2334
site location*fertilizer treatment*cultivar	6	0.5221	0.8265	0.5462	0.8646

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 4.2. Mean grain and straw potassium (K), sulfur (S), calcium (Ca) and magnesium (Mg) concentration (n=4) of four faba bean cultivars with two fertilizer treatments at four field site locations in 2016 and three field site locations in 2017.

Year	Cultivar	K	S	Ca	Mg
		g kg^{-1}			
		----Straw----			
2016	CDC Snowdrop	9.2 a†	0.3 b	4.2 ab	0.9 a
	219-16	9.0 ab	0.4 a	4.5 a	0.9 a
	Snowbird	8.1 b	0.4 ab	4.1 ab	1.0 a
	Tabasco	8.1 b	0.3 b	3.7 b	0.5 b
2017	CDC Snowdrop	14.8 a	1.9 a	5.4 a	2.0 a
	219-16	14.9 a	1.7 a	5.3 a	1.7 b
	Snowbird	13.5 a	2.0 a	4.9 a	1.7 b
	Tabasco	14.3 a	1.6 a	5.0 a	1.6 b
		----Grain----			
2016	CDC Snowdrop	10.9 a	1.9 a	1.0 a	1.4 b
	219-16	10.8 a	2.0 a	1.1 a	1.5ab
	Snowbird	10.7 a	1.8 b	0.9 b	1.5 a
	Tabasco	10.7 a	2.0 a	0.8 c	1.4 c
2017	CDC Snowdrop	8.7 b	2.0 a	0.9 ab	0.9 bc
	219-16	8.8 ab	2.0 ab	0.9 ab	0.9 ab
	Snowbird	9.0 a	1.9 b	1.0 a	1.0 a
	Tabasco	8.8 ab	2.0 ab	0.7 b	0.9 c

† Within a column, means within a yield component followed by the same letter are not significantly different from each other (p≥0.05).

Table 4.3. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial straw and grain zinc (Zn), copper (Cu) and iron (Fe) concentration.

Effect	*df*†	Zn	Cu	Fe
		---------------------------*2016*--------------------------		
		---------------------*Straw*----------------------		
site location	3	**< 0.0001**‡	0.9613	**0.0097**
fertilizer treatment	1	**0.0411**	0.8511	0.8195
site location*fertilizer treatment	3	0.1927	0.8136	0.1598
cultivar	3	**0.0085**	**0.0058**	**0.0008**
site location*cultivar	9	0.8426	0.4511	0.4222
fertilizer treatment*cultivar	3	0.8669	0.7995	**0.0383**
site location*fertilizer treatment*cultivar	9	0.6606	0.4290	0.5327
		---------------------*Grain*----------------------		
site location	3	**< 0.0001**	**< 0.0001**	**< 0.0001**
fertilizer treatment	1	0.3633	0.4727	**0.0266**
site location*fertilizer treatment	3	**0.0118**	0.2458	0.1749
cultivar	3	**0.0230**	**0.0098**	**0.0073**
site location*cultivar	9	**0.0023**	**0.0420**	0.8336
fertilizer treatment*cultivar	3	0.2763	0.4965	0.1906
site location*fertilizer treatment*cultivar	9	0.5123	0.5027	0.3121
		---------------------------*2017*--------------------------		
		---------------------*Straw*----------------------		
site location	2	**0.0012**	0.2268	**0.0115**
fertilizer treatment	1	0.3366	0.8902	**0.0028**
site location*fertilizer treatment	2	0.2556	0.2768	**0.0025**
cultivar	3	0.2989	0.1058	0.3953
site location*cultivar	6	0.4683	0.3527	0.6363
fertilizer treatment*cultivar	3	0.8746	0.9068	0.5306
site location*fertilizer treatment*cultivar	6	0.4590	0.9378	0.3679
		---------------------*Grain*----------------------		
site location	2	0.1095	**0.0080**	**0.0153**
fertilizer treatment	1	0.4899	0.2285	0.2307
site location*fertilizer treatment	2	0.6052	0.7534	0.7603
cultivar	3	0.6183	0.2370	0.4917
site location*cultivar	6	0.3684	0.4527	0.5138
fertilizer treatment*cultivar	3	0.1526	0.2291	0.5180
site location*fertilizer treatment*cultivar	6	0.8309	0.1233	0.0619

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 4.4. Mean straw and grain zinc (Zn), copper (Cu) and iron (Fe) concentration (n=4) of four faba bean cultivars with two fertilizer treatments at four field site locations in 2016 and three field site locations in 2017.

Year	Cultivar	Zn	Cu	Fe
			mg kg^{-1}	
		----------------------------*Straw*----------------------------		
2016	CDC Snowdrop	5.2 a†	1.5 b	34.4 b
	219-16	5.9 a	1.9 a	36.3 b
	Snowbird	4.9 ab	1.5 b	47.8 a
	Tabasco	3.6 b	1.2 b	31.9 b
2017	CDC Snowdrop	7.8 a	2.5 a	57.4 a
	219-16	4.9 a	2.2 ab	48.9 a
	Snowbird	5.8 a	1.7 ab	55.5 a
	Tabasco	4.9 a	1.2 b	56.5 a
		----------------------------*Grain*----------------------------		
2016	CDC Snowdrop	36.4 a	8.6 a	32.0 b
	219-16	35.2 ab	8.3 ab	30.9 b
	Snowbird	34.2 b	7.7 b	28.9 b
	Tabasco	36.2 a	7.8 b	37.5 a
2017	CDC Snowdrop	48.8 a	7.5 a	95.9 a
	219-16	49.5 a	7.3 a	87.8 a
	Snowbird	47.6 a	7.7 a	90.7 a
	Tabasco	52.7 a	8.2 a	94.3 a

† Within a column, means within a yield component followed by the same letter are not significantly different from each other ($p \geq 0.05$).

Site location influenced straw and grain uptake of K, S, and Mg in both 2016 and 2017, and straw and grain Ca uptake in 2016 and straw Ca uptake in 2017 (Tables 4.5 and 4.6), with the highest K, S, Ca and Mg uptake in faba bean generally at the Saskatoon site location in 2016 and 2017 and the lowest at the sandy textured Outlook location. As expected, fertilization with K and S increased straw and grain K and S uptake and also grain Mg uptake in 2016 and straw K uptake in 2017 (Tables 4.5 and 4.6). Generally, less response in uptake to fertilization was observed in 2017 compared to 2016. Fertilization increased straw K and S uptake at higher yielding sites in 2016 and 2017, as supported by the significant interaction between site location and fertilization for straw K and S uptake in both field study years (Table 4.5). As shown in Table 4.5, cultivar affected straw K and Mg uptake and grain Ca uptake in 2016 and straw Mg uptake in 2017. In 2016, straw K uptake was generally less in Snowbird than in other cultivars and straw Mg uptake was less in Tabasco than in other cultivars, while straw Mg uptake was greater in CDC Snowdrop. The greatest grain Ca uptake was in cultivar 219-16 in 2016 and the greatest straw Mg uptake was in cultivar CDC Snowdrop in 2017. The interaction between site location and cultivar was significant for straw K uptake and grain Ca uptake in 2016 and straw Mg uptake in 2017 (Table 4.5).

Straw and grain Zn uptake in 2016 and straw Zn uptake in 2017 (Table 4.7) were affected by site location, with the lowest Zn uptake at Outlook in 2016 and the greatest straw Zn uptake at Saskatoon in 2017. Effects on uptake are related to both yield and concentration impacts of the factors evaluated. Grain Cu uptake was affected by site location and was greater than straw Cu uptake at all sites in 2016 and 2017 and was the greatest at Saskatoon in 2016 and Rosthern in 2017. Site location also affected grain Fe uptake in 2016 and straw and grain Fe uptake in 2017, with the greatest Fe uptake at Saskatoon. Fertilization with N, P, K, S increased straw and grain Zn and Fe uptake in 2016 and grain Zn and Fe uptake in 2017 (Tables 4.7 and 4.8). Straw and grain Zn uptake and straw Fe uptake were greater in fertilized faba bean compared to unfertilized faba bean only at Saskatoon (Tables 4.7 and 4.8). Cultivar did not have an influence on uptake of any micronutrient in 2016 or 2017, but there was a significant interaction between site and cultivar for grain Zn uptake in 2016 (Table 4.7).

Table 4.5. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial straw and grain potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) uptake.

Effect	*df*†	K	S	Ca	Mg
			2016		
			Straw		
site location	3	**< 0.0001**‡	**< 0.0001**	**< 0.0001**	**0.0003**
fertilizer treatment	1	**< 0.0001**	**< 0.0001**	0.2189	0.5601
site location*fertilizer treatment	3	**0.0108**	**< 0.0001**	0.4561	0.6933
cultivar	3	**0.0365**	0.4179	0.1132	**< 0.0001**
site location*cultivar	9	**0.0171**	0.1928	0.1131	0.2856
fertilizer treatment*cultivar	3	0.7975	0.7367	0.4769	0.4132
site location*fertilizer treatment*cultivar	9	0.2702	0.3435	0.3395	0.7889
			Grain		
site location	3	**0.0003**	**0.0017**	**0.0017**	**0.0005**
fertilizer treatment	1	**0.0070**	**0.0007**	0.0516	**0.0185**
site location*fertilizer treatment	3	0.1196	0.1752	0.3233	0.3280
cultivar	3	0.9809	0.8043	**< 0.0001**	0.4046
site location*cultivar	9	0.1335	0.0777	**0.0137**	0.0851
fertilizer treatment*cultivar	3	0.8952	0.7516	0.6358	0.7889
site location*fertilizer treatment*cultivar	9	0.1226	0.3218	0.3437	0.1488
			2017		
			Straw		
site location	2	**<0.0001**	**0.0001**	**<0.0001**	**<0.0001**
fertilizer treatment	1	**0.0375**	0.3284	0.1640	0.5731
site location*fertilizer treatment	2	**0.0352**	**0.0003**	0.6744	0.8925
cultivar	3	0.0707	0.5446	0.1364	**0.0043**
site location*cultivar	6	0.2711	0.8753	0.2996	**0.0112**
fertilizer treatment*cultivar	3	0.5372	0.9294	0.4856	0.8723
site location*fertilizer treatment*cultivar	6	0.4058	0.9383	0.6637	0.9117
			Grain		
site location	2	**0.0026**	**0.0002**	0.0542	**0.0041**
fertilizer treatment	1	0.1002	0.2592	0.0815	0.0766
site location*fertilizer treatment	2	0.5271	0.3088	0.6135	0.6233
cultivar	3	0.6592	0.2740	0.3203	0.5470
site location*cultivar	6	0.2827	0.2493	0.5237	0.4642
fertilizer treatment*cultivar	3	0.8617	0.8282	0.5278	0.9399
site location*fertilizer treatment*cultivar	6	0.6400	0.8738	0.6864	0.8324

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 4.6. Mean straw and grain potassium (K), sulfur (S), magnesium (Mg) and calcium (Ca) uptake (kg ha^{-1}) by four faba bean cultivars with two fertilizer treatments at four site locations in 2016 and three site locations in 2017.

Year	Site location	Fertilizer treatment‡	K	S	Ca	Mg
			kg ha^{-1}			
			---------------------***Straw***---------------------			
2016	Meath Park	Unfertilized	39.0a†	0.6b	26.1a	3.3a
		Fertilized	60.3a	1.4a	28.8a	3.1a
	Rosthern	Unfertilized	22.1b	1.2b	16.9a	4.9a
		Fertilized	33.9a	2.4a	19.1a	5.5a
	Saskatoon	Unfertilized	78.0b	2.3b	20.3b	3.9a
		Fertilized	104.5a	5.1a	23.4a	4.2a
	Outlook	Unfertilized	17.4a	1.3a	14.1a	3.4a
		Fertilized	23.2a	1.4a	13.5a	3.4a
2017	Meath Park	Unfertilized	63.4a	4.8a	24.0a	4.2a
		Fertilized	53.3a	3.7a	24.6a	4.6a
	Rosthern	Unfertilized	30.2b	3.4b	15.1a	7.5a
		Fertilized	47.0a	5.0a	17.5a	8.2a
	Saskatoon	Unfertilized	117.7a	24.0a	36.2a	15.3a
		Fertilized	149.0a	19.0a	41.0a	15.3a
			---------------------***Grain***---------------------			
2016	Meath Park	Unfertilized	55.1a	9.0b	4.8a	6.5a
		Fertilized	67.4a	12.4a	5.7a	7.7a
	Rosthern	Unfertilized	63.3a	11.2a	4.7a	8.9a
		Fertilized	70.5a	12.4a	5.2a	9.8a
	Saskatoon	Unfertilized	63.0b	11.1b	5.5a	8.7b
		Fertilized	75.5a	12.7a	6.1a	9.7a
	Outlook	Unfertilized	32.8a	6.0a	3.4a	4.7a
		Fertilized	32.6a	6.1a	3.3a	4.6a
2017	Meath Park	Unfertilized	37.7a	8.2a	4.0a	3.8a
		Fertilized	38.3a	8.0a	4.3a	3.9a
	Rosthern	Unfertilized	38.6a	8.4a	3.4a	4.2a
		Fertilized	44.5a	10.2a	3.8a	4.8a
	Saskatoon	Unfertilized	56.6a	13.5a	4.8a	5.6a
		Fertilized	62.2a	13.9a	6.6a	6.3a

† Within a column, means within a site followed by the same letter are not significantly different from each other ($p \geq 0.05$).

‡ Fertilized treatments received N, P, K, S fertilizer prior to planting.

Table 4.7. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial straw and grain zinc (Zn), copper (Cu) and iron (Fe) uptake.

Effect	*df*†	Zn	Cu	Fe
		2016		
		Straw		
site location	3	**< 0.0001**‡	0.1504	0.0993
fertilizer treatment	1	**0.0211**	0.2687	**0.0300**
site location*fertilizer treatment	3	**0.0336**	0.8904	**0.0449**
cultivar	3	0.6893	0.3172	0.3896
site location*cultivar	9	0.5973	0.5489	0.4603
fertilizer treatment*cultivar	3	0.7392	0.4939	0.2875
site location*fertilizer treatment*cultivar	9	0.5559	0.6281	0.2905
		Grain		
site location	3	**< 0.0001**	**< 0.0001**	**< 0.0001**
fertilizer treatment	1	**0.0082**	0.1551	**0.0112**
site location*fertilizer treatment	3	**0.0002**	0.3661	0.1210
cultivar	3	0.7283	0.8152	0.1024
site location*cultivar	9	**0.0039**	0.0728	0.3871
fertilizer treatment*cultivar	3	0.9683	0.6543	0.6892
site location*fertilizer treatment*cultivar	9	0.0727	0.3227	0.4981
		2017		
		Straw		
site location	2	**<0.0001**	0.2000	**0.0017**
fertilizer treatment	1	0.7105	0.8846	0.3058
site location*fertilizer treatment	2	0.4734	0.5778	0.0888
cultivar	3	0.2294	0.0624	0.1871
site location*cultivar	6	0.8749	0.2709	0.2049
fertilizer treatment*cultivar	3	0.8972	0.9358	0.0729
site location*fertilizer treatment*cultivar	6	0.4350	0.8293	0.1937
		Grain		
site location	2	0.1930	**0.0046**	**0.0006**
fertilizer treatment	1	**0.0254**	0.7695	**0.0104**
site location*fertilizer treatment	2	0.6597	0.3812	0.6371
Cultivar	3	0.4665	0.1181	0.5758
site location*cultivar	6	0.3753	0.3514	0.9377
fertilizer treatment*cultivar	3	0.2721	0.3992	0.8411
site location*fertilizer treatment*cultivar	6	0.8727	0.3549	0.2963

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 4.8. Mean straw and grain zinc (Zn), copper (Cu) and iron (Fe) uptake (kg ha^{-1}) by four faba bean cultivars with two treatments at four site locations in 2016 and three site locations in 2017.

Year	Site location	Fertilizer treatment‡	Zn	Cu	Fe
			kg ha^{-1}		
			-----------------***Straw***-----------------		
2016	Meath Park	Unfertilized	0.02a†	0.01a	0.13a
		Fertilized	0.04a	0.01a	0.15a
	Rosthern	Unfertilized	0.04a	0.01b	0.22a
		Fertilized	0.04a	0.01a	0.22a
	Saskatoon	Unfertilized	0.02b	0.01a	0.14b
		Fertilized	0.04a	0.01a	0.23a
	Outlook	Unfertilized	0.00a	0.01a	0.16a
		Fertilized	0.01a	0.01a	0.19a
2017	Meath Park	Unfertilized	0.03a	0.00a	0.10a
		Fertilized	0.01a	0.01a	0.13a
	Rosthern	Unfertilized	0.02a	0.01a	0.27a
		Fertilized	0.02a	0.01a	0.22a
	Saskatoon	Unfertilized	0.05a	0.01a	0.50a
		Fertilized	0.05a	0.01a	0.46a
			-----------------***Grain***-----------------		
2016	Meath Park	Unfertilized	0.21a	0.04a	0.21b
		Fertilized	0.25a	0.04a	0.29a
	Rosthern	Unfertilized	0.26a	0.05a	0.09a
		Fertilized	0.27a	0.05a	0.13a
	Saskatoon	Unfertilized	0.22b	0.07b	0.24b
		Fertilized	0.26a	0.07a	0.28a
	Outlook	Unfertilized	0.07a	0.02a	0.07a
		Fertilized	0.06a	0.01a	0.06a
2017	Meath Park	Unfertilized	0.22a	0.03a	0.35a
		Fertilized	0.23a	0.03a	0.39a
	Rosthern	Unfertilized	0.23a	0.05a	0.38b
		Fertilized	0.28a	0.05a	0.49a
	Saskatoon	Unfertilized	0.26b	0.04a	0.61a
		Fertilized	0.32a	0.04a	0.70a

† Within a column, means within a site followed by the same letter are not significantly different from each other ($p \geq 0.05$).

‡ Fertilized treatments received N, P, K, S fertilizer prior to planting.

4.5.1.2 Post-harvest available soil sulfate, potassium, zinc, copper and iron

Available soil SO_4 content post-harvest was significantly affected by site location at all three soil depths (0-15 cm, 15-30 cm and 30-60 cm) in 2016 and 2017, except at the 0-15 cm depth in 2017 (Table 4.9), with the greatest available soil SO_4 at the Saskatoon site location in both study years, consistent with presence of subsoil salinity at this site. When averaged across all site locations in 2016 and 2017, available soil SO_4 was greater in fertilized field plots than in unfertilized plots at the 0-15 cm and 15-30 cm soil depths in 2016 but was more variable in 2017 with no significant differences among treatments at each site (Tables 4.9 and 4.10).

Table 4.9. Type III fixed effects ANOVA *p* value summary for available soil sulfate (SO_4) at three soil depths (0-15, 15-30, 30-60 cm) in 2016 and 2017 field trials.

Effect	***df*†**	**0-15 cm**	**15-30 cm**	**30-60 cm**
			SO_4	
			2016	
site location	3	**< 0.0001‡**	**< 0.0001**	**< 0.0001**
fertilizer treatment	1	**< 0.0001**	**< 0.0001**	0.6211
site location*fertilizer treatment	3	**< 0.0001**	**0.0023**	0.0932
Cultivar	3	0.6528	0.2646	0.8675
site location*cultivar	9	0.3180	0.3087	0.8841
fertilizer treatment*cultivar	3	0.9427	0.2205	0.8747
site location*fertilizer treatment*cultivar	9	0.5132	0.5589	0.6829
			2017	
site location	2	0.0609	**0.0003**	**<0.0001**
fertilizer treatment	1	0.1629	0.0894	**0.0072**
site location*fertilizer treatment	2	**0.0083**	0.2580	**0.0228**
Cultivar	3	0.7477	0.5992	0.7990
site location*cultivar	6	0.2276	0.5284	0.7806
fertilizer treatment*cultivar	3	0.8223	0.6417	0.5733
site location*fertilizer treatment*cultivar	6	0.2819	0.3841	0.6456

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference (p≥0.05).

Table 4.10. Mean available soil sulfate (SO_4) (n=4) at three soil depths (0-15, 15-30 and 30-60 cm) with two fertilizer treatments at the 2016 and 2017 site locations after harvest.

Year	Site location	Fertilizer treatment†	0-15 cm	15-30 cm	30-60 cm
			SO_4		
			kg ha^{-1}		
2016	Meath Park	Unfertilized	3.6b‡	3.0b	4.8b
		Fertilized	5.5a	7.0a	11.2a
	Rosthern	Unfertilized	9.7b	8.4b	20.2a
		Fertilized	16.0a	17.7a	32.4a
	Saskatoon	Unfertilized	11.4b	15.7a	96.1a
		Fertilized	18.5a	23.8a	78.5a
	Outlook	Unfertilized	5.2a	7.8a	24.3b
		Fertilized	3.5a	9.5a	39.6a
2017	Meath Park	Unfertilized	13.7a	7.5a	9.9a
		Fertilized	8.6a	5.9a	12.4a
	Rosthern	Unfertilized	9.4a	9.2a	99.7a
		Fertilized	18.1a	7.7a	76.0a
	Saskatoon	Unfertilized	174.3a	399.2a	1556.7a
		Fertilized	54.9a	194.0a	768.8a

† Fertilized treatments received N, P, K, S fertilizer prior to planting.

‡ Within a column, means within a site location followed by the same letter are not significantly different from each other ($p \geq 0.05$).

Extractable available soil K and micronutrients (Zn, Cu and Fe) were affected by site location at the 0-15 cm soil depth in 2016 (Table 4.11), with Saskatoon field plots having greater available soil K and Cu and Outlook field plots with their sandy soil texture having less available soil K and micronutrients than other sites (Table 4.12). Site location also affected available soil K and Fe at the 0-15 cm soil depth in 2017, with greater available soil K at Saskatoon and greater available soil Fe at Meath Park compared to other sites. Fertilization increased post-harvest available soil K at the 0-15 cm soil depth in 2016 but had no significant effect on available K in 2017 (Table 4.11). Cultivar also had no significant effect on available K and neither fertilization or cultivar affected available soil micronutrients at the 0-15 cm soil depth in either study year (Table 4.11).

Table 4.11. Type III fixed effects ANOVA *p* value summary for soil extractable available potassium (K), copper (Cu), zinc (Zn) and iron (Fe) in the 0-15 cm soil depth in 2016 and 2017 field trials.

Effect	*df*†	K	Zn	Cu	Fe
	------------------------------*2016*----------------------------				
site location	3	**< 0.0001**‡	**0.0008**	**< 0.0001**	**< 0.0001**
fertilizer treatment	1	**< 0.0001**	0.4450	0.9654	0.9375
site location*fertilizer treatment	3	**0.0420**	0.2987	0.3792	**0.0287**
cultivar	3	0.9084	0.2641	0.4558	0.4537
site location*cultivar	9	0.2516	0.1417	0.7921	0.6595
fertilizer treatment*cultivar	3	0.9828	0.8828	0.9101	0.9309
site location*fertilizer treatment*cultivar	9	0.8582	0.8242	0.9527	0.9852
	------------------------------*2016*----------------------------				
site location	2	**0.0002**	0.0587	0.2701	**0.0002**
fertilizer treatment	1	0.5607	0.4152	0.6495	0.5962
site location*fertilizer treatment	2	0.6573	0.8924	0.1229	0.7247
cultivar	3	0.6373	0.2066	0.9877	0.1746
site location*cultivar	6	0.0825	0.2988	0.7124	0.4871
fertilizer treatment*cultivar	3	0.8139	0.7308	0.6055	0.4397
site location*fertilizer treatment*cultivar	6	0.1207	0.0756	0.4162	0.1960

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table 4.12. Mean available extractable soil potassium (K), copper (Cu), zinc (Zn) and iron (Fe) (n=4) in the 0-15 cm soil depth at the four 2016 and three 2017 field site locations after harvest.

Year	Site	K	Zn	Cu	Fe
		kg ha^{-1}			
2016	Meath Park	417.8b†	4.0 a	0.7c	165.1a
	Outlook	264.5c	1.0 b	0.5d	13.3b
	Rosthern	425.9b	3.9 a	1.6b	140.5a
	Saskatoon	949.3a	3.6 a	1.9a	127.9a
2017	Meath Park	495.9b	4.8 a	1.4a	217.0a
	Rosthern	440.9b	2.6 b	1.4a	121.2b
	Saskatoon	958.0a	3.4ab	1.5a	76.8c

† Within a column, means within a field study year followed by the same letter are not significantly different from each other ($p \geq 0.05$).

4.6 Discussion

4.6.1 Faba bean macronutrient and micronutrient concentration

4.6.1.1 Field study faba bean macronutrient (potassium, sulfur, magnesium and calcium) and micronutrient (zinc, copper and iron) concentration

Faba bean macro- and micronutrient concentration is an important element of crop nutrition. Whether nutrient concentration is measured in faba bean grain to assess the mineral content and nutritional value of faba bean for human or animal consumption or in faba bean straw to assess the potential nutrient contribution and agronomic benefits of faba bean straw to succeeding crops, it is important to know the nutrient content in the different components of a faba bean crop being grown in rotation. Currently, there are no studies in western Canada that include measurements of faba bean macro- and micronutrient concentration that could be compared with results from the current field study. Because of this, a study in Germany conducted by Makkar et al. (1997), a field study in southern Italy conducted by Cazzato et al. (2012) and a recent field study conducted by Etemadi et al. (2018) in Massachusetts, USA, will be roughly compared with the results from the current field study to show the effects of cultivar and fertilization on faba bean grown in different countries under different conditions.

From the results of the study conducted in Germany that measured faba bean nutrient content in white-flowering and colour-flowering faba bean cultivars grown at different breeding stations, Makkar et al. (1997) discovered that faba bean grain mineral content was generally influenced by cultivar. Similarly, faba bean grain nutrient concentration in the current study varied between cultivars for all nutrients (S, Ca, Mg, Zn, Cu and Fe) except K in 2016 and for only Mg concentration in 2017. Faba bean grain macronutrient content for the six white-flowering cultivars measured by Makkar et al. (1997) ranged from: 1.7 to 2.2 g S kg^{-1}, 12.1 to 14.9 g K kg^{-1}, 1.3 to 2.1 g Ca kg^{-1} and 0.2 to 1.7 g Mg kg^{-1}. Grain micronutrient content for the same cultivars ranged from: 41.0 to 63.2 mg Zn kg^{-1}, 8.9 to 21.1 mg Cu kg^{-1} and 49.9 to 68.9 mg Fe kg^{-1}. These results were compared with average grain macronutrient concentration for the four zero-tannin cultivars from the current study that ranged from: 1.8 to 2.0 g S kg^{-1}, 8.7 to 10.9 g K kg^{-1}, 0.7 to 1.1 g Ca kg^{-1} and 0.9 to 1.5 g Mg kg^{-1}, and average grain micronutrient concentration that ranged from: 34.2 to 52.7 mg Zn kg^{-1}, 7.3 to 8.6 mg Cu kg^{-1} and 28.9 to 95.9 mg Fe kg^{-1}, with grain Zn and Fe concentration greatly varying between site years. Though S and Mg concentration of white-flowering/zero-tannin faba bean in both studies were similar, K, Ca, Zn and Cu were less in the current study. Interestingly, Fe concentration of faba bean cultivars grown in the 2016 site year of the current study were less than Fe content of faba bean assessed in the study by Makkar et al. (1997), but Fe concentration of faba bean cultivars in the 2017 site year of the current study were greater. The vast difference in concentrations of the same nutrient from year to year emphasizes the importance of evaluating faba bean cultivars at different site locations in different site years and considering the varying effects that different conditions can have on faba bean crops.

Cazzato et al. (2012) evaluated the effects of three different S fertilizer rates on grain nutrient concentration of one faba bean cultivar at one site location in southern Italy, while the current study evaluated the effect of unfertilized and fertilized treatments on four different faba bean cultivars at four different site locations in Saskatchewan. Though faba bean nutrient concentrations of the two studies cannot be directly compared because of their differences, including being conducted under different countries and conditions, applying different types of fertilizer at different rates and evaluating a different number of cultivars, the two studies were generally compared to show the effects of fertilization and fertilization rates on faba bean nutrient concentration. Average faba bean grain K and Ca concentrations measured by Cazzato et al. (2012) were 10.7 g K kg^{-1} and 1.7 g Ca kg^{-1}, and were greater than average grain K and Ca concentrations of the unfertilized and fertilized treatments in the current study that were 9.8 g K kg^{-1} and 0.9 g Ca kg^{-1}, but grain Fe concentration was 0.06 g kg^{-1} in both studies. Cazzato et al. (2012) found that as S fertilization rate increased, K and Ca concentration in faba bean grain increased significantly, but S fertilization rate had no effect on Fe concentration in grain. Interestingly, the two nutrient concentrations, K and Ca, that were greater in the study in southern Italy compared to the current study were also the two nutrient concentrations that were significantly greater with increasing S fertilization rate in the study in southern Italy. In the current study, fertilization with N, P, K and S significantly increased grain K and Fe concentrations in 2016 but had no effect on grain K and Fe in 2017, or grain Ca in either study year. Different conditions and slightly different site locations in the two years of the current study likely influenced the difference in effect of fertilization on K and Fe concentration from 2016 to 2017, but with only one year of study to measure nutrient concentration in, it is unclear whether the effect of S fertilization rate on K and Ca concentration that Cazzato et al. (2012) discovered was due to the conditions in the study year or whether the same effect would occur in a succeeding study year.

When average unfertilized faba bean grain micronutrient concentrations measured by Etemadi et al. (2018) in the USA and measured in the current study were compared, grain Zn and Fe concentrations were greater in the current study and grain Cu concentration was less. The average unfertilized faba bean grain Zn, Cu and Fe concentrations measured by Etemadi et al. (2018) were 40 mg Zn kg^{-1}, 20 mg Cu kg^{-1} and 71 mg Fe kg^{-1}, and the average unfertilized faba bean grain Zn, Cu and Fe concentrations in the current study were 49 mg Zn kg^{-1}, 8 mg Cu $kg^{-1}$and 90 mg Fe kg^{-1}. Etemadi et al. (2018) compared micronutrient concentrations in faba bean grain, leaves and pods and found that Zn concentration was greatest in grain, Cu concentration was equal in grain and leaves, and Fe concentration was greatest in leaves. Though the current study did not compare micronutrient concentrations in faba bean grain with concentrations in faba bean leaves or pods, the majority of faba bean Zn, Cu and Fe content was also in faba bean grain, which was compared with faba bean straw. It can be noted that faba bean plots were harvested before leaves senesced and before pods and grain dried out in the field study conducted by Etemadi et al. (2018), whereas faba bean plots were harvested after most leaves had senesced and after pods and grain had dried out in the current field study. Therefore, it is possible that the faba bean plants in the current study had greater average Zn and Fe content because they had more time to take up Zn and Fe before they reached full maturity.

4.6.2 Faba bean macronutrient and micronutrient uptake

4.6.2.1 Field study faba bean macronutrient (potassium, sulfur, calcium, magnesium) and micronutrient (zinc, copper and iron) uptake and partitioning

Most recent faba bean studies in western Canada focus on yield and/or biological nitrogen fixation (BNF). For faba bean, there are relatively few published studies in general on nutrient elements apart from N and P which can be used to compare the results of the K, S, Ca, Mg, Zn, Cu, Fe assessments made in the current study, and no studies from western Canada. Instead, results will be compared mainly to studies conducted outside of Canada such as a field study in Germany conducted by Pötzsch et al. (2018) in 2012 to 2014, and a field study conducted in Denmark (Jensen et al., unpublished) as reported in a global review of faba bean by Jensen et al. (2010). It should be noted that these studies were conducted under different conditions than the current study and assess uptake differently, so a direct comparison of the studies is not possible, but a general comparison is made to consider differences in uptake of the same nutrients but under different conditions.

At several sites throughout Germany, S requirements of faba bean were assessed in a study with different forms of S fertilizer applied on long-term (>10 years) organically cultivated crop land (Pötzsch et al., 2018). They found that S accumulation in faba bean shoot ranged from 9 to 11 kg S ha^{-1} and in faba bean grain ranged from 6 to 7 kg S ha^{-1}. The straw S uptake at different site locations in the current study was relatively low in 2016, with a greater range in 2017 compared to that reported by Pötzsch et al. (2018), ranging from 1.0 to 3.7 kg ha^{-1} at the four 2016 field site locations and from 4.1 to 21.4 kg ha^{-1} at the three 2017 field site locations. The levels of available S in the soil varied more among sites in our Saskatchewan study, especially related to varying levels of subsoil sulfate ($SO^{-2}{}_4$) salts, explaining the greater range in the current study. However, average grain S uptake at the site locations in the current study was more consistent among locations and closer to that found by Pötzsch et al. (2018), ranging from 6.1 to 11.9 kg S ha^{-1} in 2016 and from 8.1 to 13.7 kg S ha^{-1} in 2017. However, not only was grain S uptake for the current study greater than grain S uptake in the study by Pötzsch et al. (2018), but it was also greater than faba bean grain S uptake reported to range from 3.1 to 10.6 kg S ha^{-1} in a study that assessed S fertilization and inoculation of faba bean, conducted by Habtemichial et al. (2007) in semi-arid Northern Ethiopia in 2004 and 2005. Differences in shoot/straw and grain S uptake in the faba bean grown in these international studies compared to Saskatchewan were not surprising considering the difference in environments where the faba beans were grown and the difference in fertilizer type and rate applied, but it can be noted that grain S uptake by Saskatchewan grown faba bean was greater than in the other studies in different locations around the world. This means that more S is also removed from the field in faba bean grain harvest, which should be considered when assessing soil fertility and using a maintenance approach in order to maintain a critical level of available S in the soil to supply requirements of faba bean and the crops that follow faba bean in rotation.

Jensen et al. (2010) reported average faba bean K, Ca and Mg uptakes from a study in 1985 as 190 kg K ha^{-1}, 102 kg Ca ha^{-1} and 18 kg Mg ha^{-1}, for a faba bean crop with average total dry matter (stubble+empty pods+grain) of 12,400 kg ha^{-1} grown in a sandy loam soil in Denmark with no added N fertilizer or with 50 kg N ha^{-1} added N fertilizer. The average aboveground (straw+grain) biomass of faba bean in the current study (10,400 kg ha^{-1}) was less than the biomass reported by Jensen et al. (2010), as were the corresponding average faba bean K, Ca and Mg uptakes of 124 kg K ha^{-1}, 28 kg Ca ha^{-1} and 13 kg Mg ha^{-1} when compared with nutrient uptakes reported by Jensen et al. (2010). Similarly, average straw nutrient uptake in the current study was less than empty pod and stubble nutrient uptake reported by Jensen et al. (2010), with considerably lower K and Ca uptake and slightly lower Mg uptake in the current study. Jensen et al. (2010) reported empty pod and stubble K, Ca and Mg uptakes of 128 kg K ha^{-1}, 98 kg Ca ha^{-1} and 12 Mg kg ha^{-1}, while straw K, Ca and Mg uptakes in the current study were 62 kg K ha^{-1}, 23 kg Ca ha^{-1} and 7 kg Mg ha^{-1}. Interestingly, average grain uptakes in the current study were similar to grain nutrient uptakes reported by Jensen et al. (2010), with higher grain K uptake in the Denmark study than in the current study, but almost equal grain Ca and Mg uptake. Jensen et al. (2010) reported grain K, Ca and Mg uptakes of 63 kg K ha^{-1}, 5 kg Ca $ha^{-1}$and 6 kg Mg ha^{-1}, and in the current study the grain K, Ca and Mg uptakes were 52 kg K ha^{-1}, 5 kg Ca $ha^{-1}$and 7 kg Mg ha^{-1}. The inclusion of empty pods and leaves along with straw and grain in average dry matter and nutrient uptake measurements by Jensen et al. (unpublished) may explain the greater dry matter yield and nutrient uptake values in the study reported by Jensen et al. (2010) compared to the straw and grain biomass included in biomass and nutrient uptake measurements in the current study. However, there are likely other factors (e.g. cultivar, environment) that could contribute to the difference in values as well.

Considering faba bean macronutrient uptake and partitioning in the present study, the results indicate that faba bean are high K users, with about half of the total aboveground faba bean K uptake contained in grain in 2016 and less than half in grain in 2017. It was also indicated that faba bean grain had greater S uptake than straw at all 2016 site locations and at the site locations with lower total S uptake in 2017. This is supported by a faba bean study conducted in Germany from 2012 to 2014 by Pötzsch et al. (2018), who also found greater S uptake in faba bean grain and calculated a S harvest index (HI) of 0.65. A high content of S containing amino acids found in protein of pulse grain, pods and leaves would explain the high S content in faba bean grain (Sexton et al., 1998; Pötzsch et al., 2018). In contrast to S uptake, the majority of Ca and Mg uptake in aboveground biomass in the current study was found in faba bean straw in both study years. For faba bean micronutrient (Zn, Cu, Fe) uptake and partitioning in the present study, overall average aboveground (straw+grain) faba bean Zn uptake was 0.26 kg ha^{-1}, Cu uptake was 0.05 kg ha^{-1} and Fe uptake was 0.56 kg ha^{-1}, with most Zn and Cu uptake in faba bean grain in 2016 and 2017 and most Fe uptake in faba bean grain in 2017 for all cultivars at all site locations, whether faba bean was unfertilized or fertilized.

4.6.2.2 Field study faba bean macronutrient (potassium, sulfur, magnesium and calcium) and micronutrient (zinc, copper and iron) uptake compared to other pulses

Field study experiments comparing faba bean to other pulses are limited in western Canada, especially ones comparing the macronutrients K, S, Ca and Mg or micronutrients such as Zn, Cu and Fe. Faba bean in the 1985 field study in Denmark (Jensen et al., unpublished) reported in the global review by Jensen et al. (2010) also made comparisons with pea in the same study. In the Denmark study, faba bean K and Mg uptake in aboveground (stubble+empty pods+grain) dry matter and residue (stubble+empty pods) were greater than pea K and Mg uptake, and the same trend may be expected for faba bean and pea grown in Saskatchewan conditions.

Average nutrient uptake of other pulses (soybean, pea, lentil) in a field study at four site locations in Saskatchewan conducted by Xie (2017) in 2014 can also be generally compared to average faba bean nutrient uptake at the different site locations in the current study, though the two studies were not conducted in the same years at all of the same site locations. Straw K uptake in faba bean in the current study ranged from 20 to 134 kg ha^{-1} and was generally similar to straw K uptake reported for soybean, pea and lentil by Xie (2017), but the range of straw K uptake in faba bean was greater than the range reported for the other three pulses. The faba bean straw S uptake was generally higher than soybean and lentil straw S uptake, but the range of faba bean straw S uptake was less than, and generally lower than, pea straw S uptake. Faba bean straw Ca uptake (14 to 39 kg ha^{-1}) and straw Mg uptake (3 to 15 kg ha^{-1}) were lower than straw Ca and Mg uptake in soybean and pea but was similar to straw Ca and Mg uptake in lentil, though slightly lower than lentil straw Ca uptake. Grain macronutrient uptake and removal by each pulse crop was also compared. Faba bean grain K uptake (33 to 69 kg ha^{-1}) and Mg uptake (4 to 9 kg ha^{-1}) in the current study were generally greater than soybean and pea grain K and Mg uptake and consistently greater than lentil grain K and Mg uptake as measured by Xie (2017). Faba bean grain Ca uptake ranged from 3 to 6 kg ha^{-1} and was similar, but slightly less than soybean grain Ca uptake, generally greater than pea grain Ca uptake and consistently greater than lentil grain Ca uptake. Growing faba bean in rotation may therefore contribute to accelerated depletion in base cation soil fertility compared to other annual legume crops, even compared to soybean which was identified as a high base cation user (Xie, 2017). Grain S uptake in faba bean ranged from 6 to 14 kg ha^{-1} and was generally greater than in soybean, pea and lentil.

For the micronutrient metals, grain Zn uptake in faba bean ranged from 0.1 to 0.3 kg ha^{-1} and was greater than in soybean, pea and lentil, and straw Zn uptake in faba bean ranged from 0.005 to 0.05 kg ha^{-1} and was less than in soybean, pea and lentil. Faba bean grain Cu uptake ranged from 0.01 to 0.07 kg ha^{-1}, was similar to pea grain Cu uptake and was generally greater than soybean and lentil grain Cu uptake, but straw Cu in faba bean uptake that ranged from 0.005 to 0.01 kg ha^{-1} was less than in soybean, pea and lentil. Growing high yielding faba beans with their higher content and partitioning of Zn and Cu in grain may lead to more rapid depletion of these micronutrients in soil from grain harvest compared to other pulse crops.

4.7 Conclusion

As observed for concentration and uptake of N and P reported in Chapter 3, considerable variation was also observed for other macro- and micronutrients in different locations and in different years. Soil and environmental conditions need to be taken into account. For example, faba bean grown at the Saskatoon site location had greater K and S concentration in both 2016 and 2017 reflecting high soil available K and S at this location. As well, concentration of K, S, Ca and Mg in faba bean straw and grain components were influenced by site-year. Site also significantly affected macronutrient (K, S, Ca and Mg) and micronutrient (Zn, Cu and Fe) total uptake in different yield components depending on the site-year. The greatest faba bean total K, S, Ca and Mg uptake occurred at the Saskatoon site location in 2016 and 2017 with the highest micronutrient uptake varying between site-years. While the majority of the average S uptake was found in grain in many site-years, the majority of Zn and Cu uptake was in grain and majority of Ca uptake was in straw in all site-years. The partitioning of faba bean uptake of K, Mg and Fe between grain and straw was dependent on site-year, but overall, uptake of K was fairly evenly divided between the grain component and the straw component.

The significant effects of fertilization on nutrient concentration and uptake and of cultivar on nutrient uptake were also influenced by site-year. Faba bean straw and grain K, S and Fe concentration were increased by fertilization in 2016, but only grain S concentration was increased in 2017. Fertilization also significantly increased K, S, Mg, Zn and Fe uptake to varying extents depending on site-year, with significantly greater straw K and S uptake at higher yielding sites in 2016 and 2017 and significantly greater Zn and Fe uptake at different site locations in 2016 and 2017. Cultivar affected straw or grain K, Ca and Mg uptake depending on the field study year but did not affect micronutrient uptake in either 2016 or 2017.

When results from the current field study were compared with similar international studies (Makkar et al., 1997; Cazzato et al., 2012; Etemadi et al., 2018), reported mineral content in faba bean was greatly dependent on the location of the other studies and the conditions in that location. While faba bean concentration of certain macro- and micronutrients were similar between the current study and the international studies, the differences in nutrient content were inconsistent. There were not enough field studies to compare whether the same was true for faba bean macro- and micronutrient uptake. In the studies that could be compared, grain K, Ca and Mg uptakes in the current study were similar to grain uptakes in an earlier field study in Denmark while grain S uptake for the current study was greater than grain S uptake in faba bean studies in other countries. Overall, faba bean macronutrient (K, S, Ca and Mg) uptake in the grain in the current study was generally greater than or similar to macronutrient uptake by other pulses (soybean, pea and lentil) reported in a recent field study in Saskatchewan conducted at similar locations (Xie, 2017), but differences in straw macronutrient uptake between the two studies were inconsistent which is attributed to straw nutrient content being more sensitive to soil and environmental conditions than grain. Similarly, grain micronutrient (Zn, Cu and Fe) uptake by faba bean in the current study was similar to or greater than micronutrient uptake in the other Saskatchewan pulse study but straw micronutrient uptake was consistently less in faba bean than in soybean, pea and lentil. Overall, large amounts of K, moderate amounts of S, and most of the aboveground (straw+grain) Zn and Cu taken up by faba bean, were removed in faba bean grain at harvest. Faba bean yield components showed limited response to fertilization, but fertility management in rotations with faba bean will need to consider drawdown of base cations, S and micronutrients over the long-term.

5. SYNTHESIS AND CONCLUSION

5.1 Overview

The research in this M.Sc. thesis explores the plant nutrient content and soil fertility related aspects of growing modern faba bean cultivars in the western Canadian prairies. The information obtained on faba bean yield, nutrient uptake and removal as affected by site location, fertilization, and cultivar will be useful for growers who include, or plan to include, faba bean in their rotation, and for researchers looking to further investigate the role of faba bean crops in soil fertility management in the region. The studies are the first to document faba bean yield, macro- and micronutrient requirements and removals in Saskatchewan, and provide estimates of the proportion of nitrogen derived from atmosphere (%Ndfa) through biological nitrogen fixation (BNF) in response to P fertilization. More specifically, this research reports on straw and grain yield, macronutrient (N, P, K, S, Ca, Mg) and micronutrient (Cu, Zn, Fe) concentration and uptake, as affected by four modern faba bean cultivars, two fertilizer treatments (unfertilized and fertilized with N, P, K and S), from field studies conducted at four site locations in the Dark Grey, Black and Dark Brown soil-climatic zones in south-central Saskatchewan in 2016 and 2017. The site locations were chosen based on regions where faba bean crops are typically grown in Saskatchewan. In addition, this research provides information on above- and belowground yield, N and P concentration and uptake, and aboveground %Ndfa and contribution of BNF as affected by three P fertilizer rates and two cultivars, using ^{15}N-labelled urea and the ^{15}N isotope dilution method in a glasshouse study conducted in 2017. Information on soil available nutrients measured pre-seeding and post-harvest are also reported for the field and glasshouse studies.

5.2 Key Findings and Conclusions

The field studies with faba bean discussed in Chapter 3 revealed high yield potential of the four modern zero tannin faba bean cultivars, with no significant differences in straw yield or grain yield for the four cultivars (CDC Snowdrop, 219-16, Snowbird, Tabasco) or the two fertilizer treatments (unfertilized and fertilized) at the four site locations in 2016 (Meath Park, Rosthern, Saskatoon, Outlook) and the three site locations in 2017 (Meath Park, Rosthern, Saskatoon). Average grain N (117-300 kg N ha^{-1}) and grain P (15-36 kg P ha^{-1} or 34-82 kg P_2O_5 ha^{-1}) uptake by faba bean were generally greater than grain N and P uptake by pulses in other Saskatchewan field studies. Average N harvest index (NHI: 86-94%) and P harvest index (PHI:

85-96%) were also greater in the current study than previously reported. A significant amount of external N from biological nitrogen fixation (BNF) likely contributed to high yield potential, with an average of 88 %Ndfa by faba bean estimated based on results from the glasshouse study, similar to the median value of 88 %Ndfa by faba bean reported by Walley et al. (2007) in the northern Great Plains.

The large amounts of N, P, and K, moderate amounts of S, and majority of aboveground (straw+grain) Zn and Cu found in faba bean grain in the current field studies points towards high crop removal potential from grain harvest. The average kilograms (kg) of aboveground (straw+grain) faba bean nutrient uptake per tonne of faba bean grain yield are summarized in Table 5.1, showing similar aboveground requirements per unit of yield among site locations, fertilizer treatment and cultivar. An average of about 44 kg N, 12 kg P_2O_5, 26 kg K_2O and 3 kg S were contained in aboveground faba bean biomass per tonne of grain yield produced.

Table 5.1. Mean aboveground (grain+straw) nutrient uptake per unit of faba bean grain yield (kg tonne^{-1}) at Meath Park, Rosthern, Saskatoon and Outlook site locations in 2016 and 2017.

Site location	Fert trt†	N	P	K	S	Ca	Mg	Zn	Cu	Fe
		kg tonne^{-1}								
		---2016---								
Meath Park	Unfertilized	41.0	5.3	17.8	1.8	5.9	1.9	0.04	0.009	0.07
	Fertilized	40.7	5.9	20.7	2.3	5.8	1.8	0.05	0.009	0.07
Rosthern	Unfertilized	42.5	4.2	13.2	1.9	3.3	2.1	0.05	0.009	0.05
	Fertilized	42.7	4.5	15.1	2.1	3.5	2.2	0.05	0.009	0.05
Saskatoon	Unfertilized	45.7	5.8	25.6	2.4	4.7	2.3	0.04	0.014	0.07
	Fertilized	45.8	6.2	29.5	2.9	4.9	2.3	0.05	0.014	0.08
Outlook‡	Unfertilized	45.1	6.0	17.1	2.4	5.8	2.7	0.02	0.007	0.09
	Fertilized	46.3	6.3	18.8	2.5	5.7	2.6	0.02	0.006	0.09
		---2017---								
Meath Park	Unfertilized	42.6	5.2	24.9	3.1	6.9	2.0	0.06	0.009	0.11
	Fertilized	43.9	4.5	20.7	2.6	6.7	2.0	0.05	0.008	0.12
Rosthern	Unfertilized	44.6	3.9	15.5	2.7	4.2	2.6	0.05	0.013	0.15
	Fertilized	44.7	4.0	18.1	3.0	4.2	2.6	0.06	0.012	0.14
Saskatoon	Unfertilized	45.4	5.3	28.1	6.1	6.5	3.4	0.05	0.008	0.19
	Fertilized	44.8	5.1	31.2	4.9	7.1	3.2	0.06	0.007	0.17

† Fert trt = fertilizer treatment. Fertilized treatments received N, P, K, S fertilizer prior to planting.

‡ Plots at the Outlook site location were affected by strong winds in spring 2016 and were not harvested in 2017 due to extensive hail damage.

Because the estimated proportion and amount of N removed in grain harvest was similar or greater than that estimated to be derived from fixation in the plant, the net positive addition of N to the system through BNF is limited when the faba bean grain is harvested. These results suggest that unless faba bean grain is left unharvested and the entire plant is returned and incorporated into the soil, there would be no significant addition of N to the cropping system from BNF by faba bean. However, results from the glasshouse study show that an average of 20% of total faba bean N and 14% of total faba bean P were measured in belowground plant material in the form of roots. This suggests that aboveground N and P uptake measurements typically underestimate total amounts of N and P contained in the crop and which are left behind in the soil after harvest that could potentially contribute to future crops.

The results of the two-year field studies reveal variations across site locations and years which imply that faba bean nutrient concentration and uptake is affected by varying soil and environmental conditions. Additionally, faba bean grown on soils with good fertility showed limited response to P, K and S fertilization, and no large differences were observed in faba bean nutrient uptake or response to fertilization among the four different cultivars, suggesting that nutrient requirements were relatively similar among the cultivars. Interestingly, yield and BNF by faba bean did respond positively to P fertilization when grown on a P deficient soil in the glasshouse study, and yield, %Ndfa, amount of Ndfa (mg pot^{-1}) and N and P uptake were significantly greater in the smaller seeded cultivar CDC Snowdrop. These results indicate that optimization of P fertility is important in obtaining maximum yield and BNF in faba bean. The differences in BNF and response to P fertilization observed among faba bean cultivars in the glasshouse study deserves further research attention.

5.3 Recommendations and Future Research

Quantification of nutrient uptake and BNF are two factors that can aid in sound management of fertility in faba bean containing rotations on the Canadian prairies. This includes knowing the nutrients removed and those that need to be replaced following faba bean in rotation, often in the form of mineral fertilizer. Although some have used grain yield from the previous crop as a basis for making fertilizer recommendations for the succeeding crop in rotation, grain yield alone typically gives an inaccurate estimation of N or other nutrients removed by a crop (Walley et al., 2007). Results from the current field and glasshouse studies do suggest that high N, P, K removals in faba bean grain are closely associated with high yields and high concentration in grain. Therefore, information on yield, nutrient concentration and uptake, estimated BNF (%Ndfa and amount of Ndfa) by faba bean in the current studies should help more effectively estimate how much N and other mineral fertilizer needs to be added to the crops in the following growing seasons. A direct assessment of this in the field via growing various crops after faba bean and measuring their yield and nutrient uptake would be useful. Based on the nutrient uptake results in this thesis research, it is recommended that fertility management in rotations with faba bean consider soil nutrient balances, especially the drawdown of P in the soil, and the requirements for added fertilizer over the long-term, due to most of the N, P, S, Zn and Cu taken up being found in grain.

Though the current study effectively quantifies nutrient uptake in faba bean, BNF estimates in this study come from glasshouse experiment results rather than field scale faba bean crops. When BNF is accurately quantified, reported values of nutrient uptake and removal by crops from the soil contribute more effectively to the assessment of the agronomic and environmental benefits of different cropping systems (Anglade et al., 2015). In order to more effectively assess the agronomic performance of faba bean at a field scale, it is recommended that BNF should be measured at the field scale, much like it was for pulses in another field study in Saskatchewan (Xie, 2017).

Currently, the results of the field study research show that faba bean grain micronutrient (Zn, Cu and Fe) uptake was similar or greater than other pulses in the study conducted by Xie (2017), but straw micronutrient uptake was less in faba bean. Therefore, it is likely that faba bean straw would return lower amounts of micronutrients to the soil than other pulses, due to the majority of micronutrient uptake being removed in faba bean grain. Also, considering about 20% of total plant N and 14% of total plant P was in faba bean roots in the current glasshouse study, and considering roots are potentially a source of available N and P to future crops because they remain in the soil after harvest, the potential contribution of N and P in faba bean roots should also be considered, along with other macro- and micronutrients. The assessment of faba bean residue (straw, pods and leaves), stubble and roots would all aid in increasing the understanding of how faba bean crops contribute nutrients in crop rotations over a longer period of time than just the season they are grown in, as compared to other pulse crops. The number of rotational cycles and crop rotations in the comparisons should be increased, with more extreme growing conditions, including both irrigated and dryland production of faba bean.

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APPENDIX

Table A.1. Pre-seeding available nutrients (n=10) in the 0-15 cm soil depth at four 2016 and 2017 field site locations. Manganese (Mn) and boron (B) are available forms measured using methodologies described in the text.

Site location	2016		2017	
	Mn	B	Mn	B
	kg ha^{-1}			
Meath Park	54	3.7	90	7.1
Rosthern	75	8.9	75	6.7
Saskatoon	76	7.7	66	5.3
Outlook	21	9.4	-†	-

† The 2017 Outlook site location faba bean crop was later destroyed by hail.

Table A.2. Mean straw, grain and total yield (n=4) of four faba bean cultivars with two treatments applied at four field site locations in 2016 and 2017.

Site location	Fertilizer treatment†	2016			2017		
		Yield					
		Straw	Grain	Total	Straw	Grain	Total
		kg ha^{-1}					
Meath Park	Unfertilized	4158	5285	9443	4296	4120	8416
	Fertilized	4866	5984	10850	4413	4456	8869
Rosthern	Unfertilized	5095	6481	11575	4074	4555	8629
	Fertilized	5622	6928	12550	4480	5161	9641
Saskatoon	Unfertilized	6715	5574	12289	6111	6301	12411
	Fertilized	7681	6145	13826	6797	6859	13656
Outlook	Unfertilized	3796	3099	6896	-‡	-	-
	Fertilized	3714	3085	6799	-	-	-

† Fertilized treatments received N, P, K, S fertilizer prior to planting.

‡ Plots at the Outlook site location were affected by strong winds in spring 2016 and were not harvested in 2017 due to extensive hail damage. Data not available.

Table A.3. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial yields.

Effect	*df*†	Yield		
		Grain	**Straw**	**Total**
		------------------------***2016***------------------------		
site location	3	0.1980	0.2174	0.2319
fertilizer treatment	1	0.2754	0.3110	0.2868
site location*fertilizer treatment	3	0.5511	0.6197	0.5653
cultivar	3	0.2486	0.9892	0.4606
site location*cultivar	9	0.5593	0.4078	0.4025
fertilizer treatment*cultivar	3	0.6504	0.6996	0.6774
site location*fertilizer treatment*cultivar	9	0.4888	0.4852	0.4477
		------------------------***2016***------------------------		
site location	2	0.1926	0.1873	0.1890
fertilizer treatment	1	0.3109	0.3996	0.3446
site location*fertilizer treatment	2	0.9062	0.8015	0.8568
cultivar	3	0.6719	0.5961	0.7189
site location*cultivar	6	0.5992	0.4852	0.6403
fertilizer treatment*cultivar	3	0.8194	0.7793	0.8283
site location*fertilizer treatment*cultivar	6	0.8014	0.7492	0.7799

† *df* = numerator degrees of freedom.

Table A.4. Type III fixed effects ANOVA *p* value summary for 2016 and 2017 field trial harvest indices (HI).

Effect	***df*†**	**HI**
		%
		-------2016-------
site location	3	**<0.0001**‡
fertilizer treatment	1	0.0957
site location*fertilizer treatment	3	0.9578
cultivar	3	**<0.0001**
site location*cultivar	9	0.0790
fertilizer treatment*cultivar	3	0.1248
site location*fertilizer treatment*cultivar	9	0.1163
		-------2017-------
site location	2	**0.0350**
fertilizer treatment	1	0.6773
site location*fertilizer treatment	2	0.5719
cultivar	3	**0.0070**
site location*cultivar	6	**<0.0001**
fertilizer treatment*cultivar	3	0.1657
site location*fertilizer treatment*cultivar	6	0.0709

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference ($p \geq 0.05$).

Table A.5. Fall residual soil nitrate (NO_3) and sulfate (SO_4) (n=4) in three soil depths at four 2016 and three 2017 field site locations. Nitrate and sulfate are available forms measured using methodologies described in the text.

Site location	Fertilizer treatment†	Depth	2016		2017	
			NO_3	SO_4	NO_3	SO_4
		cm	----------------------kg ha^{-1}----------------------			
Meath Park	Unfertilized	0-15	4.4	3.6	6.3	13.7
		15-30	3.3	3.0	1.7	7.5
		30-60	4.3	4.8	2.7	9.9
	Fertilized	0-15	5.6	5.5	7.6	8.6
		15-30	3.3	7.0	2.0	5.9
		30-60	4.3	11.2	3.3	12.4
Rosthern	Unfertilized	0-15	14.9	9.7	2.9	9.4
		15-30	8.4	8.4	1.6	9.2
		30-60	13.2	20.2	7.6	99.7
	Fertilized	0-15	14.5	16.0	2.2	18.1
		15-30	7.9	17.7	1.1	7.7
		30-60	12.0	32.4	9.4	76.0
Saskatoon	Unfertilized	0-15	12.5	11.4	11.1	174.3
		15-30	7.1	15.7	6.1	399.2
		30-60	9.7	96.1	8.5	1556.7
	Fertilized	0-15	14.3	18.5	10.1	54.9
		15-30	7.9	23.8	4.9	194.0
		30-60	10.6	78.5	8.9	768.8
Outlook	Unfertilized	0-15	7.2	5.2	-‡	-
		15-30	5.8	7.8	-	-
		30-60	13.5	24.3	-	-
	Fertilized	0-15	6.7	3.5	-	-
		15-30	6.3	9.5	-	-
		30-60	17.0	39.6	-	-

† Fertilized treatments received N, P, K, S fertilizer prior to planting.

‡ Plots at the Outlook site location were affected by strong winds in spring 2016 and were not harvested in 2017 due to extensive hail damage. Data not available.

Table A.6. Fall residual soil nutrients (n=4) in the 0-15 cm soil depth at the four 2016 and three 2017 field site locations. Phosphorus (P), potassium(K), copper (Cu), zinc (Zn) and iron (Fe) are extractable, available forms measured using methodologies described in the text.

Year	Site location	Fertilizer treatment†	P	K	Cu	Zn	Fe
			kg ha^{-1}				
2016	Meath Park	Unfertilized	35	373	0.7	3.9	165
		Fertilized	46	462	0.7	4.0	165
	Rosthern	Unfertilized	36	407	1.6	3.9	147
		Fertilized	53	445	1.5	3.9	134
	Saskatoon	Unfertilized	42	915	1.8	3.3	122
		Fertilized	52	984	1.9	3.8	134
	Outlook‡	Unfertilized	26	254	0.5	1.1	14
		Fertilized	33	275	0.5	1.0	13
2017	Meath Park	Unfertilized	38	502	1.4	4.6	222
		Fertilized	33	489	1.3	4.9	212
	Rosthern	Unfertilized	19	422	1.4	2.6	112
		Fertilized	30	460	1.4	2.7	130
	Saskatoon	Unfertilized	50	948	1.4	3.1	68
		Fertilized	67	968	1.6	3.7	85

† Fertilized treatments received N, P, K, S fertilizer prior to planting.

‡ Plots at the Outlook site location were affected by strong winds in spring 2016 and were not harvested in 2017 due to extensive hail damage. Data not available.

Table A.7. Belowground yield and nitrogen (N) components (n=4) of two faba bean cultivars and three phosphorus (P) fertilizer treatments in 2017 glasshouse faba bean P response study. Outliers (<0 % or mg pot^{-1}) were removed before mean values were calculated.

Cultivar	Fertilizer treatment	Yield	N Yield	N	Ndfa†	Ndfa†	Ndff†	Ndfs†
	mg P kg soil^{-1}	g pot^{-1}	mg pot^{-1}	-----%------		--------mg pot^{-1}--------		
CDC Snowdrop	0	2.7	56.5	2.2	47.2	26.8	1.6	28.1
	15	2.8	58.7	2.1	43.3	24.4	1.8	32.5
	30	2.6	55.1	2.1	30.5	16.1	1.6	36.8
Snowbird	0	2.0	37.9	1.9	37.1	15.7	1.2	21.0
	15	2.4	44.7	1.8	46.9	26.4	1.4	24.3
	30	2.2	38.6	1.8	33.6	12.8	1.1	24.7

† %Ndfa = proportion of nitrogen derived from atmosphere; Ndfa (mg pot^{-1}) = nitrogen derived from atmosphere; Ndff = nitrogen derived from fertilizer; Ndfs = nitrogen derived from soil.

Table A.8. Type III fixed effects ANOVA *p* value summary for proportion (%) of belowground nitrogen (BGN) per nitrogen (N) uptake and belowground phosphorus (BGP) per phosphorus (P) uptake of faba bean in 2017 glasshouse study.

Effect	***df*†**	**BGN**	**BGP**
		% N uptake^{-1}	**% P uptake^{-1}**
cultivar	1	0.5648	0.9053
fertilizer treatment	2	**0.0254**‡	**0.0004**
cultivar*fertilizer treatment	2	0.8576	0.3526

† *df* = numerator degrees of freedom.

‡ Bolded values denote significant difference (p≥0.05).