Soybean Response to Potassium Fertility and Fertilizer in Manitoba

by

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

MASTER OF SCIENCE

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ABSTRACT

Production of soybean [*Glycine max* (L.) Merr], a high potassium (K) consuming crop (18 – 23 g K_2O kg^{-1} or 1.1 – 1.4 lb K_2O bu^{-1}), has rapidly expanded in Manitoba in recent years. However, there has been little comprehensive historical K fertility research for soybean in the province. A two-year study was developed to assess the frequency of soybean yield response to K fertilization and determine the effectiveness of K fertilizer rate and placement combinations for increasing seed yield. The study included small plot trials, field scale on-farm trials and paired microplots within each on-farm trial.

Small plot trials were primarily used to determine the efficacy of different K fertilizer rate and placement combinations (33 or 66 kg K_2O ha^{-1} sidebanded, and 33, 66 or 132 kg K_2O ha^{-1} broadcast and incorporated) for improving seed yield. Although the potential for K fertilizer response was present at midseason in some site-years, as indicated by an increase in tissue K concentration of the whole plant (WP), uppermost mature trifoliate (UMT) leaves and the stem, there was no significant seed yield response to K fertilization at any small plot site-year.

On-farm trials were used to investigate the frequency of soybean response to K fertilization across a range of NH_4OAc soil test K (STK) concentrations (52 – 451 mg kg^{-1}), and microplots within on-farm trials were used to investigate the response relationships at a more detailed scale. Three out of nineteen site-years had significant seed yield responses to K fertilization at a field-scale; one response was negative and two were positive. In the microplots, the potential for fertilizer K response was also present in some site-years at midseason with increases in UMT K concentration. However, the site-years with midseason tissue K responses did not have significant seed yield differences at maturity. There were two site-years that did have a significant yield increase with K fertilization in microplots, but these were not site-years

where K fertilization increased midseason tissue K concentrations. Consistent with the small plot and field scale results, there was no significant relationship between STK and relative seed yield in the microplots.

ACKNOWLEDGMENTS

My master's experience would not have been the same without all the wonderful people involved along the way. To my university "dad", Don, thank you for your unending support, wisdom and inspiration. I would not be the young scientist I am today without your guidance. Your advising is unparalleled and irreplaceable. Thank you for sidetracking my plans to complete an MSc elsewhere, I wouldn't have had it any other way.

To my "real" dad, thank you for encouraging me to explore the world of agriculture. Your gentle nudge in this direction opened up a whole new realm of possibilities in my life. Thank you for your support, interest and dedication to my success. To my mom, brother and close friends, thank you for helping me through this journey. I appreciate each of you greatly.

To the fantastic people I have met along the way, and to those I am lucky enough to now call friends, you kept me mostly sane through this process. Lanny, you were a roommate, fellow Don-advisee, field help and support. Amy, my "big sister", your advice and expertise were valued greatly. Your work ethic, motivational. Nate, you made, and continue to make, everything more bearable. I greatly appreciate your friendship, perspective and support.

I'd also like to thank my summer students, Kris Davy and Jeremy Gladish, the soil science field technician, Trevor Fraser, and Manitoba Pulse and Soybean Growers staff for their contributions through the field seasons. Thank you to my official advisory committee members, Dr. Francis Zvomuya, Dr. Yvonne Lawley, and unofficial committee members, Kristen Macmillan and John Heard, for their advice and wisdom. Thank you to Manitoba Pulse and Soybean Growers and Western Grains Research Foundation for providing the main funding for this project, as well as Nutrien, Dekalb and Western Ag for their support.

FOREWORD

This thesis was written in compliance with the Department of Soil Science Thesis Guidelines and the Canadian Journal of Soil Science Operations Manual. I was responsible for all field work and data collection for the intensively managed small plot trials discussed in Chapter 2. I was also responsible for the design, establishment, and implementation of paired microplots and data collection from those microplots in each on-farm trial, discussed in Chapter 3, as well as the barley soybean K responsiveness comparison study discussed in the Appendix.

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1. INTRODUCTION

Globally, soybean [*Glycine max* (L.) Merr] is an important oilseed crop and protein source for both human and animal consumption. Soybean accounts for 60% of global oilseed production (Imas and Magen 2015) and is the main source of vegetable oil and protein for animal feed (Balboa et al. 2018). In Canada, between 2006 and 2017, there was a 123% increase in soybean production (Soy Canada 2019), likely due to a combination of genetic improvements for modern soybean cultivars and the need to diversify crop rotations. Now, over ten million metric tonnes of soybean are produced in Canada on an annual basis and the province of Manitoba (MB) is responsible for about 30% of that total annual production (Soy Canada 2019). In 2019, MB harvested 1.9 million acres of soybeans, occupying about 19% of the province's annual cropland (Statistics Canada 2019). This level of soybean production is new, relative to historical annual averages for MB's harvested land area (Fig. 1.1). The large and rapid expansion of soybean production in recent years offers benefits to producers in terms of diversity in rotations and markets. However, even though soybean yields have varied, soybean removes potassium (K) at a much greater rate than most other field crops grown in MB (Fig. 1.2). Thus, K nutrition of soybean is of particular interest due to this very high K removal per kg or bushel of grain at harvest (18 – 23 g K_2O kg^{-1} or 1.1 – 1.4 lb K_2O bu^{-1}) (Kaiser 2017, Manitoba Agriculture 2007). Questions about proper K fertility management for soybean production in MB are especially relevant to production areas with coarse textured soils that may be inherently low in K.

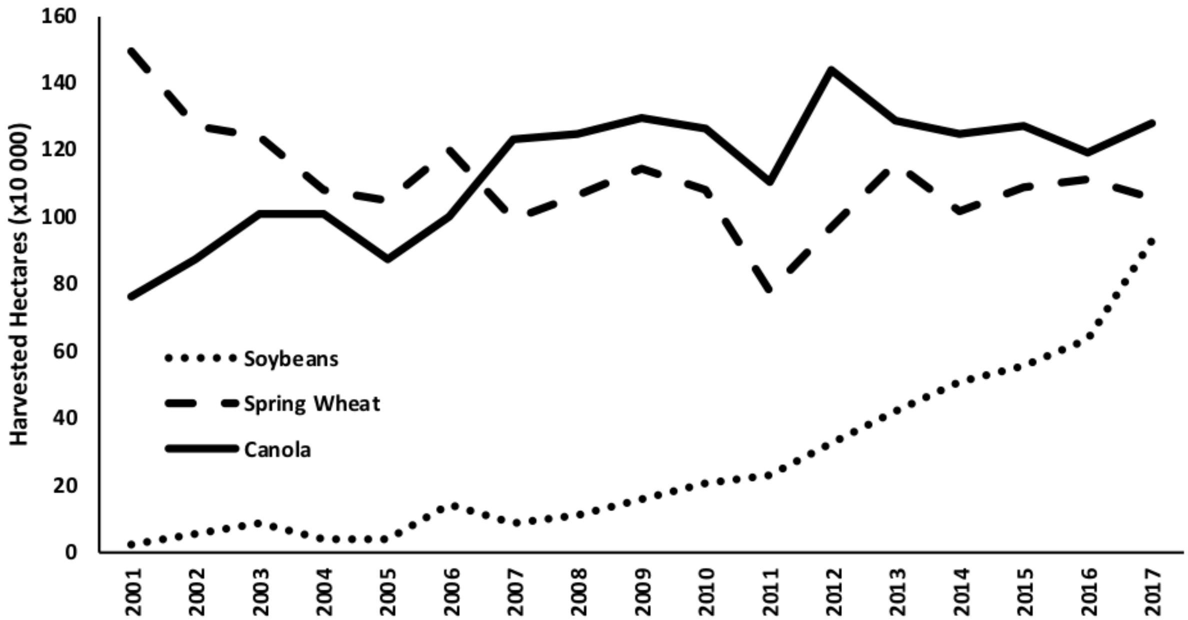

Figure 1.1 Harvested hectares of major Manitoba crops from 2001 to 2017 (Statistics Canada 2018)

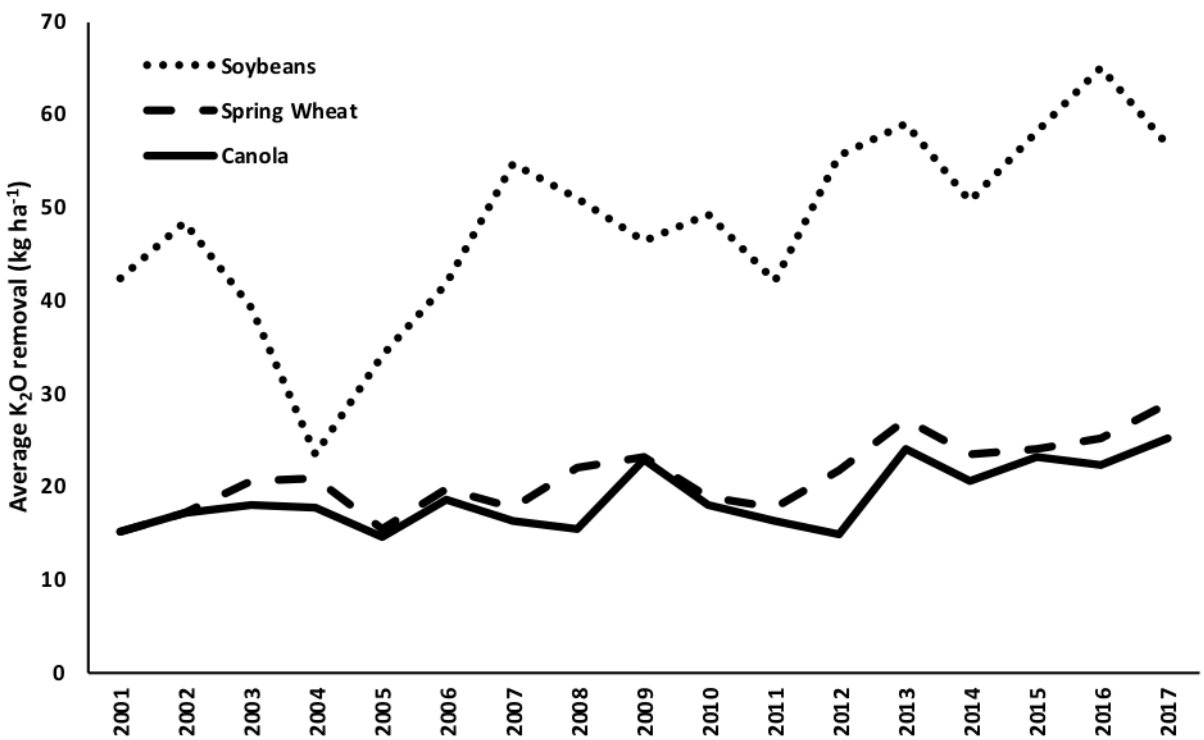

Figure 1.2 Average annual K_2O removal for major Manitoba crops from 2001 to 2017 (Manitoba Ag 2007, Statistics Canada 2018)

1.1 Soil Potassium Pools and Dynamics

1.1.1 Soil Potassium Pools

Potassium is often abundant in soils. However, the majority of soil K exists in forms that are not readily available for plant uptake (McLean and Watson 1985). A large quantity of soil K is part of the mineral structure of soils and is not available to plants until weathering occurs (Song and Huang 1985). A study of 102 soils in the U.S. found upwards of 90% of total K to be in mineral form (Sharpley 1989). Generally, there are four distinct soil K pools: solution K, exchangeable K, nonexchangeable K and structural K. In some cases, particularly when discussing relative availability of the pools, solution and exchangeable K may be grouped together and referred to as available K, while nonexchangeable may also be known as slowly available K (Murrell 2018). Although there may be large quantities of total soil K, quantifying the relative abundances, availabilities and dynamics of the pools is integral to developing adequate K fertility practices for crop production.

The solution K pool consists of water-soluble K^+ ions in the soil solution that are immediately available for plant uptake. However, solution K is a very small portion of total soil K and is not enough to support plant growth, even for a single growing season (Sparks and Huang 1985). As plant uptake occurs, exchangeable K replenishes the solution K pool. Exchangeable K is adsorbed to exchange sites in soil and is readily desorbed in exchange for other ions. As plant uptake depletes solution K, desorption replenishes this pool and is thus considered an integral part of plant available K in soil (McLean and Watson 1985). In contrast, K that is adsorbed in nonexchangeable surface complexes, commonly referred to simply as nonexchangeable K, consists of K^+ ions that are adsorbed so strongly or inaccessibly that they do not readily participate in exchange reactions or enter solution to replenish depleted water-soluble

K (McLean and Watson 1985). Lastly, there is the structural K pool. Structural K is a fundamental part of the structure of primary minerals such as K-bearing micas and feldspars (Sparks and Huang 1985). This form of K is not available for plant uptake or to participate in exchange reactions until chemical, physical or biological weathering facilitate release from the mineral structure (Sparks and Huang 1985).

1.1.2 Soil Potassium Dynamics

Despite the characterization of soil K into four distinct pools, these designations are not static in agricultural soils. Potassium additions and removals from the soil-plant system affect the quantity of K in each of the four pools, and the manner of dynamic shifts in relative abundance of each form of soil K. Differences in soil mineralogy are often the fundamental basis for differences in inherent soil K fertility level as well as a governing factor in K behaviour and dynamics. The main mineral groups of concern for K dynamics and fertility are the K-bearing feldspars and the micaceous minerals (Sparks and Huang 1985). During the formation of K feldspars, K^+ ions occupy positions in this primary mineral's framework structure to neutralize the negative charge that arises from isomorphous substitution (Sparks and Huang 1985). Micaceous minerals are layered silicates composed of two tetrahedral sheets with an octahedral sheet in the middle. As with K-feldspars, during formation, the K ion is taken into the mineral to neutralize negative layer charge that may originate as a result of isomorphous substitution, except that in micaceous minerals, these K^+ ions can be bound in the space between the unit layers (Sparks and Huang 1985). The location of the negative layer charge in the octahedral and tetrahedral sheets of micaceous minerals, in addition to the total quantity of negative charge, are factors that influence K retention. Negative charge originating in the tetrahedral layer exerts a greater force on cations occupying the interlayer space, as this charge acts over a shorter distance than octahedral charge (Florence et al. 2017). Micaceous minerals commonly found in agricultural soils include mica, illite, vermiculite and smectites.

Potassium "fixation" is a physical process which traps K^+ ions in the interlayer space of minerals, resulting in nonexchangeable adsorption of the K^+ ions. This fixation results from greater attraction between the interlayer charge and the cation than between the cation and its water shell, leading to dehydration and interlayer collapse (Florence et al. 2017). Fixation of added K is not a new phenomenon and was discovered when soluble K added to soils subsequently could not be fully recovered (Joffe and Kolodny 1936). Potassium fixation depends on a number of factors including mineralogy, extent and distribution of negative layer charge, availability of interlayer space for occupation by K ions, availability of K^+ in solution to be fixed and the concentration of competing cations (Sparks and Huang 1985).

Potassium dynamics, the fluxes of K between pools and the distribution of added K among the soil K pools, including the process of K fixation, are influenced by mineralogy. For example, even within the family of micaceous minerals, there are differences in K behaviour. Vermiculite fixes more K than smectite, likely due to the higher layer charge of vermiculite (Florence et al. 2017), which increases the capacity for adsorption of positive ions to neutralize the layer charge. Mica, as a primary mineral, has fixed interlayer K to maintain electroneutrality and also has a high layer charge, greater than both vermiculite and smectite; however, the degree to which a micaceous mineral will fix additional K will depend on the extent of saturation of K fixation sites (Florence et al. 2017). Although most K fixation studies focus on fine textured soils or soil mineral components, coarse particles, especially those containing vermiculite, could also have a large capacity to fix added K (Murashkina et al. 2007). For example, in granitic alluvium derived soils of California, the very fine and fine sand fractions have the ability to fix substantial amounts of added K (Murashkina et al. 2007).

Exchangeable K alone is usually the proxy for bioavailable K, used both to indicate the K nutrition status of a given soil and further, to make K fertilizer recommendations. However, bioavailable K is not exclusively comprised of soil K measured by simple exchange reactions. Some proportion of the nonexchangeable K pool will add to the bioavailable K for a given growing season, as the nonexchangeable K pool is in equilibrium with available K and some of the nonexchangeable K thereby contributes directly to crop K nutrition (Cox et al. 1996). So, although some portion of added K will become nonexchangeably fixed, it will not remain fixed indefinitely. Nonexchangeable K can be released to replenish the available K pools, but, to facilitate release, there needs to be drawdown of available K. A study in Sweden found greatest release of nonexchangeable K in soils where no fertilizer K was added (Simonsson et al. 2007), increasing the demand for soil K as plant K uptake was not satisfied by an addition of K fertilizer. Release also depends on the intensity of the cropping system and crop choice, which influences solution K drawdown and, therefore, how much nonexchangeable K could be demanded by the crop (During and Duganzich 1979).

The dynamic factors of soil mineralogy, texture and biology of the soil and crop interact to determine the rate and extent of nonexchangeable K release to the available K pool (Simonsson et al. 2007). The quantity and extent of nonexchangeable K contribution to crop nutrition depends on soil type and mineralogy (Murrell 2018). Soil type influences the relative sizes of the K pools, and soils with larger nonexchangeable K pools relative to the exchangeable K pool may be able to better buffer changes in the latter (Moody and Bell 2006). Exhaustive cropping experiments, such as successive cuttings of a forage, can investigate the relative amount of nonexchangeable and structural K that may become available over time as solution and exchangeable K are depleted by plant uptake. After exhaustively cropping alfalfa for 16 successive cuttings in 12 different soils, Havlin and Westfall (1985) found soil texture influenced the ability of a given soil to continue to support plant growth, as solution and exchangeable K were depleted. They found that, generally, clay soils could replenish available K, while sandy textured soils could not maintain the level of available K required by the alfalfa plants. In addition to the biological influence of crop uptake on potential nonexchangeable K release, organic acids commonly present in the soil solution, such as oxalic and citric acids, can also lead to K release from mineral structures (Song and Huang 1988). Thus, plant root extrusion of organic acids may also be an important consideration for the release of nonexchangeable or structural K, and replenishment of available K for plant uptake.

In addition to the quantity of K present in the slowly available pool, the K supplying power of a soil is also influenced by the rate at which exchangeable and solution K are replenished (Song and Huang 1988). An important process governing the ability of a given soil to moderate changes in solution K is K buffering capacity. A larger K buffering capacity results in less change in the size of the soluble K pool, because the soil can resist these changes by readily replenishing solution K (Florence et al. 2017). Potassium buffering capacity is proportional to soil cation exchange capacity (CEC) (Sparks and Huang 1985) and the CEC will also influence the quantity of K in solution. Soils with a higher CEC hold more K on exchange sites and, therefore, have less solution K than a soil with lower CEC (Bell et al. 2009). This effect is evident in comparing solution and exchangeable K quantities in kaolinitic soils, which have low CEC, and smectitic soils, which have high CEC. Smectitic soils will have more exchangeable K relative to solution K, whereas kaolinitic soils will have greater solution K relative to exchangeable K (Sharpley 1989). In addition, there is a greater diffusive ability for K in a soil with lower K buffering capacity than in a soil with higher K buffering capacity (Bell et al. 2009). This can have implications for the efficacy of K management practices, such as banding versus broadcast placement, discussed below.

1.1.3 Quantifying Plant Available Soil Potassium

Commercial laboratories testing producer soil samples generally use extraction procedures that measure the available K pool, as solution and exchangeable K. Routine use of more in-depth procedures to quantify nonexchangeable K is not common (McLean and Watson 1985). A typical extraction for determining available K is the neutral 1 M ammonium acetate (NH_4OAc) test, conducted on an air dried and ground soil sample (McLean and Watson 1985; Barbagelata and Mallarino 2012; Breker 2017). However, there is debate about the accuracy of available K determined on a sample that has undergone the physical process of drying. The drying process can alter the structure of soil minerals, inducing either K release or fixation, depending on the nature of the physical change to mineral structure. According to McLean and Watson (1985), soils with a high concentration of exchangeable K tend to fix K upon drying, reducing the exchangeable K pool, whereas soils with a low concentration of exchangeable K tend to release K as a result of scrolling and fracturing of mineral layers due to the physical process of drying. Research in Iowa has suggested that fertilizer recommendations based on extraction of NH_4OAc exchangeable K for dried soils are inferior to those based on extraction for field moist soils, due to a change in the quantity of exchangeable K resulting from the drying process (Barbagelata and Mallarino 2012). In their study, Barbagelata and Mallarino (2012) found K extracted from a dried soil was an average of 1.92 times greater than K extracted from a field moist soil, indicating an over-estimation of available K when dried soil was used. Subsequently, they found moist soil K better predicted yield response than dry soil K. This contrasts with the results of a recent study in North Dakota, which compared the standard method of NH_4OAc extraction from a dry soil with other methods, including NH_4OAc extracted from a field moist soil, resin-extracted K, and sodium tetraphenyl boron extractions (Breker et al. 2019). The current standard NH_4OAc K from a dry soil was determined to be the best method for predicting corn yield response to K fertilization. This was surprising given that extractions for solution and exchangeable K, assumed to quantify the total available K in soil, are not the total sum of bioavailable K a crop can access over the course of a growing season. The resin and tetraphenyl boron methods extract some nonexchangeable K (Breker et al. 2019), and some of this K pool is expected to become plant-available over the course of a growing season. However, inclusion of this pool in estimates of soil K status with these two methods did not improve prediction of corn yield response compared to the standard NH_4OAc K determined on a dry soil.

1.2 Plant Potassium

Similar to other soil nutrients, K can move to plant roots via three processes: root interception, mass flow and diffusion. Root interception involves the plant root directly coming into contact with K^+ ions on soil surfaces. Given the small total soil particle area plant roots directly contact, this type of uptake generally comprises a small portion of total nutrient acquisition. Mass flow of a nutrient results from water uptake by plants, but concentrations of K in solution are so small that this process also accounts for only a small portion of K uptake. Therefore, diffusion is the main process by which K moves to plant roots. As plants acquire K^+ at the root surface, a concentration gradient develops that drives diffusion of soil solution K toward the root (Barber 1985). Once uptake occurs, unlike other nutrients such as nitrogen and phosphorus which are utilized as structural components of plants, K is largely required for physiological processes and is not incorporated into structural constituents. For example, K is used for enzymatic activation, facilitating several processes including photosynthesis, protein and starch synthesis, water, nutrient and sugar transport, control of stomatal opening and crop quality [International Plant Nutrition Insitute (IPNI) 1998]. Therefore, potassium fertility influences photosynthetic and other physiological processes regulating the rate and extent of crop growth. This can have an influence on the rate of new leaf expansion early in the season, which gives plants with adequate K supply an advantage over those deficient in K (Fernández et al. 2009) through facilitating greater leaf area to increase photosynthetic capacity. Adequate K nutrition can also influence yield through increasing the number of pods and seeds per plant, as well as reducing the number of pods that do not contain seeds (Fernández et al. 2009). Additionally, K fertility may influence seed quality parameters such as seed size, shriveled seed, moldy seed, oil and protein content (Usherwood 1985).

Potassium deficiency symptoms usually manifest as interveinal chlorosis at leaf margins. If sufficient K is not accessed from the soil, these symptoms appear on lower leaves early in the season, during vegetative growth stages, as K in older plant tissue is remobilized to new growth at the top of the plant. Potassium deficiency symptoms can also be evident later in the growing season, during soybean reproductive growth stages. Development of late season deficiency symptoms can result from a change in how K is redistributed among plant parts once seed fill begins to take place (Snyder and Ashlock 1996). Unlike early season K deficiency symptoms that show on lower leaves, late season K deficiency symptoms occur in the upper canopy. These symptoms develop in plants without adequate K fertility at seed fill timing, as the K in the vegetative tissue is being redistributed to the developing seed. Deficiency symptoms in the upper canopy intensify with the extent and rate of upper canopy seed development (Snyder and Ashlock 1996).

Measures of the effect of K fertility on plant growth and composition include dry matter yield, tissue K concentration, seed yield and seed K concentration at maturity. Potassium concentration of plant tissue is typically measured for whole plant (WP) samples taken at a vegetative growth stage or uppermost mature trifoliate (UMT) leaves taken at an early reproductive stage. Tissue sampling to determine K nutrition status of soybean plants in the growing season is generally not used to identify and correct a deficiency that exists in the current year, but rather to adjust K fertility practices for future years. A recent study quantifying K uptake and partitioning over the growing season found soybeans stopped extracting K from the soil at growth stage R5.5, and that more than half of total K uptake by soybean occurred prior to growth stage R3 (Gaspar et al. 2017). This renders a late season K application relatively ineffective to correct a deficiency in that same year, as most of the plant K is taken up by the time the deficiency is assessed. Further, the limited mobility of K in the soil would also limit the efficacy of a late season application. However, tissue sampling is a valuable tool to assess current K fertility practices and inform K fertility management on an ongoing basis.

Early season dry matter yield is generally not affected by K fertilization (Clover and Mallarino 2013). However, K fertilization will often result in an increase in tissue K concentration, regardless of background soil test K level and even when there is no benefit to crop yield (Clover and Mallarino 2013). This is considered luxury consumption of a nutrient. For example, an Illinois study found increases in soybean tissue K concentration on soils with K concentrations greater than 104 mg K kg^{-1}, even when there was no associated increase in yield or seed quality (Fernández et al. 2009). Although there can be luxury consumption of K where increased uptake does not translate to increases in crop yield or quality parameters, there are instances where tissue K concentration increases are associated with yield response. In fact, Clover and Mallarino (2013) found increases in K tissue concentration of soybean to be a prerequisite of increases in yield as a result of K fertilization. If there was no difference in WP K concentration measured at V5-6, no yield response occurred. However, not every site that had an increase in tissue concentration had an increase in yield, indicating an increase in tissue K does not always translate to an increase in seed yield.

Critical concentration ranges have been established for WP samples taken at vegetative growth stages and UMT samples taken at reproductive stages. Critical concentration ranges represent the nutrient status of a given plant part; if the concentration is above the critical range, the threat of deficiency and resulting yield loss is reduced, but if the concentration is below the critical range a loss in yield is expected (Parvej et al. 2016b). Critical tissue K concentration ranges are typically established for whole plants at V5-6 growth stage (Clover and Mallarino 2013; Stammer and Mallarino 2018) and UMT leaves at R2-3 (Clover and Mallarino 2013; Parvej et al. 2016b; Stammer and Mallarino 2018). Over the season, K concentration of UMTs increases linearly to growth stage V5-7, and then may continue a linear increase or plateau until early reproductive stages R1-3, after which the concentration declines linearly (Parvej et al. 2016b). This linear decline corresponds to reallocation of plant K from leaf tissue to the developing reproductive plant parts. Therefore, sampling UMTs between R1-3 should capture vegetative K concentration at its peak.

A study in Arkansas found soybean trifoliate tissue between the R1 and R2 growth stages with concentrations of K less than 15 g kg^{-1} of dry matter generally indicated there would be a yield response to K fertilization (Slaton et al. 2010). Critical tissue K concentration ranges for soybean whole plant aboveground tissue at growth stage V5-6, and UMT leaves at R2-3, were found to be 18.9 to 22.6 g kg^{-1} and 15.6 to 22.6 g kg^{-1}, respectively (Stammer and Mallarino 2018). This recently established critical concentration range for K in UMT leaves is lower than the critical concentration of 24.3 g kg^{-1} found in Ontario soybeans (Yin and Vyn 2004); however, the Ontario study collected the leaf samples at R1.

Leaf tissue K concentration differences as a result of K fertilization are generally more frequent than responses in grain yield (Clover and Mallarino 2013) and seed K concentration (Fernández et al. 2009). Additionally, changes in oil and protein content of the seed as a result of K fertilization are also small and infrequent (Haq and Mallarino 2005; Fernández et al. 2009; Krueger et al. 2013; Miranda et al. 2014). However, grain yield increases with K fertilization are documented in the literature. Clover and Mallarino (2013) found increases in soybean yield occurred most frequently on soils testing in the less than optimum exchangeable K concentration category (<131 mg K kg^{-1}). In another study, soybean seed yield at low background K fertility (between 53 and 74 mg exchangeable K kg^{-1} in the top 10 cm) was statistically lower than seed yield at medium and high background K fertility levels (107 to 316 mg K kg^{-1} in the top 10 cm) (Fernández et al. 2009). The decline in yield was attributed to a smaller number of seeds per pod, fewer pods per plant and an increase in the number of seedless pods. The low K fertility treatment also had significantly lower seed K concentration, 15 g kg^{-1}, compared with 16 and 17 g kg^{-1} for the medium and high K fertility treatments, respectively. Another study investigating the physiological difference that results in yield loss with inadequate K fertility also found reduced pod number and increased seed abortion to be the main mechanisms facilitating yield differences, with a 13 to 15% decline in yield compared to medium and high K fertility treatments (Parvej et al. 2015). In that study, seed K concentration followed a pattern similar to yield response, with increasing seed K where K fertility level was higher. Potassium concentration of the seed ranged from 15.8 g kg^{-1} where background K concentrations were low, to 19.8 g kg^{-1} at high background K concentrations. This is consistent with literature suggesting seed K concentration differences resulting from K fertility differences between treatments are most likely to occur when yield response is present (Parvej et al. 2016a).

Assessing seed K concentration at harvest has been suggested as a tool to determine K nutrition status of the crop and whether deficiency occurred in that year (Parvej et al. 2016a). In their study, Parvej et al. (2016a) established a critical seed K concentration of 14.6 to 16.2 g kg^{-1} for soybeans grown at 24 Canadian site-years. Greater and more frequent yield response to K fertilization occurred where seed K concentrations were in the deficient range, compared to where they were considered sufficient.

1.3 Potassium Fertilizer Management

1.3.1 Potassium Fertilizer Rate

One of the components of 4R nutrient management, fertilizer rate, is an important consideration to ensure adequate supply to meet crop needs and limit over-application which may have agronomic and economic consequences. Recommended fertilizer rates are usually categorical, based on soil test nutrient levels. In the case of K, characterization of soil K fertility status and subsequent K fertilizer recommendations are usually based on concentrations of extracted solution plus exchangeable K (Breker et al. 2019). In MB, the typical extraction solution used is neutral NH_4OAc, on an air-dried soil and the current set of K fertility guidelines for soybean production in MB are based on this analysis. According to the Manitoba Soil

Fertility Guide (2007), K should be applied to soils with less than 100 mg kg^{-1} NH_4OAc exchangeable K (Manitoba Agriculture 2007). The recommended rate of broadcast and incorporated K depends on the NH_4OAc K concentration in the soil (Table 1.1). These thresholds and recommendations for K fertilization of soybean are identical to K recommendations for spring wheat, canola and other crops, all of which remove K at a lower rate than soybean. These current guidelines are not based on very extensive historical research. Bob Soper and Fran Walley, from the University of Manitoba, conducted soybean K fertility trials with Maple Amber soybeans in the early 1980s. However, only two sites were harvested for seed yield, and side banded K at rate of 50 or 100 kg K_2O ha^{-1} did not increase seed yield at either site (Walley and Soper 1985). One site was regarded as high in background K with high seed yield, and the other was quite low in K and had low seed yield. Additionally, neighbouring soybean producing areas such as Ontario, North Dakota and Minnesota have K fertility thresholds and K fertilizer recommendations that are greater than those currently recommended for Manitoba soybean production (Table 1.2). However, North Dakota recommends reducing K fertilizer rates by 1/3 if the fertilizer is banded, to account for improved efficiency.

Background K fertility concentrations, without K fertilization in the crop-year, can also influence tissue K, seed yield, K concentration and oil and protein content. Fernández et al. (2009) investigated differences in these parameters across low, medium and high K fertility soils. They found an increase in K concentration of tissue and seed with increasing soil K fertility, and increased yields.

Table 1.1 Manitoba Soil Fertility Guide K recommendations for soybean production[a]

Ammonium Acetate Soil Test K Concentration	Recommendation
>100 mg kg^{-1}	No additional K
50 – 75 mg kg^{-1}	33 kg K_2O ha^{-1} broadcast & incorporated
<25 mg kg^{-1}	66 kg K_2O ha^{-1} broadcast & incorporated

[a]Manitoba Agriculture (2007)

Table 1.2 Soil test K sufficiency thresholds and maximum rates of fertilizer recommended for neighbouring soybean producing areas

Location	Sufficiency threshold for no recommended K fertilizer addition (mg kg^{-1})	Maximum recommended rate of K fertilizer application (kg K_2O ha^{-1})
Ontario[a]	120	132
North Dakota[b]	150	101
Minnesota[c]	200	132

[a]OMAFRA (2017)
[b]Franzen (2018)
[c]Kaiser (2018)

1.3.2 Potassium Fertilizer Source

The most widely used source of fertilizer K is potassium chloride (KCl, 0-0-60). This source of K fertilizer accounts for about 95% of K fertilizer used in the United States (Stewart 1985). Alternatively, there are potassium sulphates, potassium nitrates, potassium phosphates and potassium magnesium salts (Stewart 1985), but these are very uncommon relative to the widespread use of KCl, likely because KCl is the most economical K fertilizer.

All the main K fertilizer sources are highly soluble salts. Upon addition to soil, these K fertilizers will readily dissolve to their constituent ions. The majority of the K^+ ions will be exchangeably or nonexchangeably adsorbed to soil components. The rapid dissolution presents a salt toxicity risk and can damage seedlings (Bell et al. 2009), especially for salt sensitive crops like soybean. Therefore, seed placed K is generally not recommended for soybean production. In addition, these K salts include anions (e.g. Cl^-, SO_4^{2-}) which could be beneficial nutrients.

1.3.3 Potassium Fertilizer Placement and Timing

Fertilizer placement and timing, the last two pillars of nutrient management, often must be considered together. Potassium fertilizer recommendations for soybean are generally given for broadcast and incorporated or banded placement, away from the seed, at planting. Alternatively, there are some K fertilizer sources that can be applied as a foliar application. Haq and Mallarino (2005) found soybean yield responses to foliar application of fertilizer mixtures containing a K component. However, this study did not apply foliar K alone, but in combination with other nutrients. Application timing is an important consideration for foliar placed K, as uptake is greatly reduced in reproductive growth stages. In addition to timing constraints limiting the efficacy of a foliar K application, the rate of K fertilizer required often limits the practicality of applying K exclusively via foliar fertilizer and renders soil application the best option (Imas and Magen 2015). The focus of most K fertilizer placement research for soybean, and the focus of the present research, is either band placement at planting or broadcast and incorporated placement immediately prior to planting.

A study of the effect of K fertilizer placement for maximizing wheat yield in MB found K banded with the seed was much more efficient than broadcast K for increasing seed yield (Murage 1984). More recent studies investigating K fertilizer uptake and yield responses in soybean with different application methods have found an increase in K uptake (Borges and Mallarino 2003) and increases in seed yield (Farmaha et al. 2011, 2012) with banded versus broadcast placement. Reasons for this increased uptake of fertilizer K, and yield response to K fertilization, include more root development around a concentrated K fertilizer band and reduced exposure of K fertilizer to soil, reducing potential for fixation (Bell et al. 2009; Nkebiwe et al. 2016). Additionally, below the soil surface there is improved soil moisture to facilitate fertilizer movement where K is banded, compared with broadcast applications (Farmaha et al. 2012).

Research in Australia has suggested that consideration of the K buffering capacity of a soil could be important for determining the most effective K fertilizer application method. Bell et al. (2009) found broadcast K to be sufficient for meeting crop K demands so long as it was incorporated to a depth of 10 to 15 cm and this application method was used on soils with low K buffering capacity. Alternatively, on soils with a high K buffering capacity, concentrating K fertilizer in a band could improve K fertilizer uptake (Bell et al. 2009). Older western Canadian research has documented substantial increases in crop yield response to banded versus broadcast K placement (Saskatchewan Ag Soils and Crops 1988; Manitoba Agriculture 1989). In addition to considering differences in fertilizer use efficiency and crop yield with band versus broadcast placement, depth of placement is also an important consideration. Banded K fertilizer was most effective when placed between 5 and 15 cm deep in the soil for corn production (McGonigle et al. 2015).

1.3.4 Influence of Potassium Management on Tissue, Seed Yield and Seed Quality

Potassium fertilization can influence soybean tissue K concentration (Slaton et al. 2010; Clover and Mallarino 2013; Parvej et al. 2016c; Stammer and Mallarino 2018), seed yield (Haq and Mallarino 2005; Fernández et al. 2009; Clover and Mallarino 2013; Parvej et al. 2016a) and seed K concentration (Parvej et al. 2016a; Usherwood 1985; Fernández et al. 2009). Older research has shown that K fertility affects soybean seed oil and protein content (Usherwood

1985); however, more recent research has found only small benefits of K fertility and fertilizer management on oil and protein content (Haq and Mallarino 2005; Fernández et al. 2009; Krueger et al. 2013).

Clover and Mallarino (2013) investigated the effect of increasing the rate of broadcast K fertilization, from 0 to 168 kg K ha^{-1}, on tissue K concentration in a corn-soybean crop rotation. Their study was conducted over two years; all fertilizer K was applied in the first year of the study such that any second-year crop responses to K fertilization were responses to residual K fertilizer applied in the previous year. Generally, they found linear increases in soybean leaf K with increasing K fertilizer rate, with maximum leaf K concentration at the maximum rate of fertilization. Potassium fertilizer increased soybean seed yield at 7 of 20 site-years: however, yield responses were found in all soil test K categories except “very high” (>181 mg kg^{-1}). In the first year of the study, soybean had a linear yield response at rates of K up to 103 kg ha^{-1}. In the second year of the study, soybean had a linear yield increase up to the maximum rate of K that had been applied in the first year of the study, 168 kg ha^{-1}. These responses were all for soybean following a corn crop, where the K fertilizer had been applied in the corn year. Slaton et al. (2010) also found soybean yield response to broadcast K fertilization across a range of soil K concentrations, but the frequency of response declined as K concentration increased from <91 mg kg^{-1} to >130 mg kg^{-1}. Another study investigating the effect of five rates of K fertilization (0 to 150 kg ha^{-1}) on soybean leaf tissue K concentration measured increases in tissue K with increasing rate, but the rate of K fertilization did not influence the growth stage where peak K concentration occurred (Parvej et al. 2016c); leaf K concentration peaked between R1-3, regardless of K fertilizer rate. In this same study, at two sites, seed yield was increased over the control with the addition of K fertilizer. However, the yields of all fertilized treatments were generally similar, even though background Mehlich-3 extractable K concentrations were quite low at both sites (76 mg kg^{-1} and 99 mg kg^{-1}).

Historically, banding K fertilizer either in the seedrow for tolerant crop species or away from the seed for salt sensitive crops, such as soybean, has resulted in increases in fertilizer K uptake and crop yield compared to broadcasting K. However, recent research directly comparing placement methods is limited. Borges and Mallarino (2003) compared broadcast and deep-band placement (15-20 cm) in a corn-soybean ridge till system and found banding K fertilizer was more effective for increasing K uptake than broadcasting, but yield increases were not always consistent. When K fertilizer was applied only in the soybean year of the rotation, no yield response to K fertilization occurred. However, at two of seven site-years where K fertilizer was applied only in the corn year of the rotation, there was a soybean yield response to K fertilizer. At one of the two site-years only the deep-band treatment increased yield, but at the other site-year both broadcast and deep-band K improved yield. This study also exemplifies the importance of fertilizer application timing and considering more than just the immediate crop, taking a more rotational approach to balancing K inputs and exports from the system. Another study investigating the effect of K fertilizer rate and placement on soybean K uptake and seed yield, found no effect of K fertilizer rate on seed yield (Farmaha et al. 2012). However, in comparing no-till broadcast K, no-till deep band K (15 cm deep) and strip-till deep band K (15 cm deep) treatments, they measured an increase in K uptake in the strip-till deep band treatment, which they suggested was a result of improved soil conditions for nutrient uptake with placement below the surface, increasing fertilizer contact with soil moisture and active roots. In the case of a nutrient such as K, which moves via diffusion in the soil, this exposure to moisture and active roots is essential for fertilizer uptake. A Canadian study investigated a combination of placement and timing of K fertilization for soybean at a constant fertilizer rate of 100 kg K ha^{-1} for each placement and timing combination. Comparing fall deep-band (15 cm), spring shallow-band (7.5 cm), spring surface broadcast and a no-K added control treatment, they found no increase in leaf K concentration with banded K fertilizer placement compared to broadcast placement, but K fertilization did increase leaf K compared to the control at some site-years (Yin and Vyn 2002).

Studies investigating K fertility and fertilizer effects on soybean oil and protein content have not found consistent benefits to increase these seed quality parameters. In Iowa, Haq and Mallarino (2005) compared foliar placement, broadcast and deep-banded placements and found that although there was a seed yield increase with K fertilization at some site-years, the benefits to oil and protein content were small and inconsistent. At the few site-years where there was a response in total oil or total protein, those responses weren't consistent and did not follow yield response in all cases. A study in Indiana that measured yield responses and increases in K uptake with increasing background K fertility level did not find an effect on oil and protein content of the soybean seed (Fernández et al. 2009). No change in soybean oil and protein content as a result of K fertilization occurred in a study conducted by Krueger et al. (2013), which compared three rates of broadcast K fertilizer, ranging between 0 and 132 kg K ha^{-1}.

1.4 Objectives of Potassium Fertility and Fertilizer Response of Soybean in Manitoba Study

Overall, the effects of K fertility and fertilizer on soybean tissue K concentration, seed yield and K concentration, oil and protein content are highly variable. Soil and environmental factors affect the demand for K by soybean, the uptake of K by the soybean roots and distribution of native and applied K among the soil K pools. Given the significant influence of soil type and mineralogy on K dynamics and availability, evaluation of crop K responsiveness should be conducted on a regional basis. Soybean can respond to K fertilization, but those responses are not always related to soil K concentrations. Additionally, responsiveness in one parameter, such as tissue K concentration or uptake, does not necessarily coincide with responsiveness in another parameter such as seed yield or oil and protein content.

Manitoba lacks rigorous historical K fertility and fertilizer research for soybean production. With the expansion of soybean acres and an increase in the incidence of soybean K deficiency symptoms in the province, there is a need to explore K fertility and fertilizer requirements for optimal soybean production in Manitoba. Given the lack of information about K fertilization responses for soybean production in this region, the objectives of this research were to determine both the frequency of response to K fertilization and the efficacy of K fertilizer rate and placement combinations for increasing soybean seed yield.

The frequency of response to K fertilization was investigated primarily through on-farm trials across a wide range of NH_4OAc extractable soil test K (STK) concentrations and geographic locations throughout the province. The main purpose for investigating frequency of soybean yield response to K fertilization across a range of STK was to assess whether the current 100 mg K kg^{-1} threshold for recommending an application of K fertilizer was adequate, and to investigate the relationship between STK and relative yield. Microplots within on-farm trials were selected to further investigate frequency of yield response and relationship to STK variability at this smaller spatial scale where more detailed measurements could be taken.

The efficacy of K fertilizer rate and placement to improve soybean seed yield was investigated using intensively managed small plot trials to evaluate a combination of six different rate and placement treatments, including three K fertilizer rates and two placements, compared to a zero K fertilizer control. Other soybean response parameters, including tissue K concentration, K uptake, seed K concentration and oil and protein content, were also investigated.

1.5 References

Balboa, G.R., Sadras, V.O., and Ciampitti, I.A. 2018. Shifts in soybean yield, nutrient uptake, and nutrient stoichiometry: A historical synthesis-analysis. Crop Sci. **58**: 43–54.

Barbagelata, P.A., and Mallarino, A.P. 2012. Field correlation of potassium soil test methods Based on dried and field-moist soil samples for corn and soybean. Soil Sci. Soc. Am. J. **77**: 318–327.

Barber, S.A. 1985. Potassium availability at the soil-root interface and factors influencing potassium uptake. Pages 309-326 *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI.

Bell, M.J., Moody, P.W., Harch, G.R., Compton, B., and Want, P.S. 2009. Fate of potassium fertilisers applied to clay soils under rainfed grain cropping in south-east Queensland, Australia. Aust. J. Soil Res. **47**: 60–73.

Borges, R., and Mallarino, A.P. 2003. Broadcast and deep-band placement of phosphorus and potassium for soybean managed with ridge tillage. Soil Sci. Soc. Am. J. **67**: 1920–1927.

Breker, J.S. 2017. Recalibration of soil potassium test for corn in North Dakota. M.Sc. thesis, North Dakota State University, Fargo, ND. 170 pp.

Breker, J.S., DeSutter, T., Rakkar, M.K., Chatterjee, A., Sharma, L., and Franzen, D.W. 2019. Potassium requirements for corn in North Dakota: Influence of clay mineralogy. Soil Sci. Soc. Am. J. **83**: 429–436.

Clover, M.W., and Mallarino, A.P. 2013. Corn and soybean tissue potassium content responses to potassium fertilization and relationships with grain yield. Soil Sci. Soc. Am. J. **77**: 630–642.

Cox, A.E., Joern, B.C., and Roth, C.B. 1996. Nonexchangeable ammonium and potassium determination in soils with a modified sodium tetraphenylboron method. Soil Sci. Soc. Am. J. **60**: 114–120.

During, C., and Duganzich, D.M. 1979. Simple empirical intensity and buffering capacity measurements to predict potassium uptake by white clover. Plant Soil **51**: 167–176.

Farmaha, B.S., Fernández, F.G., and Nafziger, E.D. 2011. No-till and strip-till soybean production with surface and subsurface phosphorus and potassium fertilization. Agron. J. **103**: 1862–1869.

Farmaha, B.S., Fernández, F.G., and Nafziger, E.D. 2012. Distribution of soybean roots, soil water, phosphorus and potassium concentrations with broadcast and subsurface-band fertilization. Soil Sci. Soc. Am. J. **76**: 1079–1089.

Fernández, F.G., Brouder, S.M., Volenec, J.J., Beyrouty, C.A., and Hoyum, R. 2009. Root and shoot growth, seed composition, and yield components of no-till rainfed soybean under variable potassium. Plant Soil **322**: 125–138.

Florence, A., Ransom, M., and Mengel, D. 2017. Potassium fixation by oxidized and reduced forms of phyllosilicates. Soil Sci. Soc. Am. J. **81**: 1247–1255.

Franzen, D.W. 2018. North Dakota fertilizer recommendation tables and equations. [Online] Available: https://www.ag.ndsu.edu/publications/crops/north-dakota-fertilizer-recommendation-tables-and-equations/sf882.pdf [8 May 2019].

Gaspar, A.P., Laboski, C.A.M., Naeve, S.L., and Conley, S.P. 2017. Phosphorus and potassium uptake, partitioning, and removal across a wide range of soybean seed yield levels. Crop

Sci. **57**: 2193–2204.

Haq, M.U., and Mallarino, A.P. 2005. Response of soybean grain oil and protein concentrations to foliar and soil fertilization. Agron. J. **97**: 910–918.

Havlin, J.L., and Westfall, D.G. 1985. Potassium release kinetics and plant response in calcareous soils. Soil Sci. Soc. Am. J. **49**: 366–370.

Imas, P., and Magen, H. 2015. Role of potassium nutrition in balanced fertilization for soybean yield and quality - global perspective.[Online] Available: https://pdfs.semanticscholar.org/e5c0/f01653f2288572d88460f515a3e04937b019.pdf [2 March 2020].

International Plant Nutrition Institute (IPNI). 1988. Functions of potassium in plants. [Online] Available: http://www.ipni.net/publication/bettercrops.nsf/0/64ED48A22E45ABD48525798000820367/$FILE/Better%20Crops%201998-3%20p04.pdf [5 Dec. 2017].

Joffe, J.S., and Kolodny, L. 1936. Fixation of potassium in soils. Science. **84**: 232.

Kaiser, D. 2017. Low commodity prices and fertilizer management – where do we go from here? [Online] Available: https://mawrc.org/wp-content/uploads/2017/02/0.2-Kaiser-Fertilizer Recommendations-Update.pdf [10 June 2020].

Kaiser, D.E. 2018. Soybean fertilizer recommendations. [Online] Available: https://extension.umn.edu/crop-specific-needs/soybean-fertilizer-recommendations#phosphate-and-potash-1078561 [8 May 2019].

Krueger, K., Susana Goggi, A., Mallarino, A.P., and Mullen, R.E. 2013. Phosphorus and potassium fertilization effects on soybean seed quality and composition. Crop Sci. **53**: 602–610.

Manitoba Agriculture. 1989. Potassium Facts.

Manitoba Agriculture. 2007. Manitoba Soil Fertility Guide. [Online] Available: https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/pubs/soil_fertility_guide.pdf [24 Jan. 2019].

McGonigle, T.P., and Grant, C.A. 2015. Variation in potassium and calcium uptake with time and root depth. Can. J. Plant Sci. **95**: 771–777.

McLean, E.O., and Watson, M.E. 1985. Soil measurements of plant-available potassium. Pages 277-308 *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI.

Miranda, D.H., Carvalho, M.L.M. de, Zambiazzi, E.V., Soares, I.O., Bruzi, A.T., Rezende, P.M. de, and Zuffo, A.M. 2014. Potassium fertilization and physiological soybean seed quality. Agric. Sci. **5**: 984–991.

Moody, P.W., and Bell, M.J. 2006. Availability of soil potassium and diagnostic soil tests. Aust. J. Soil Res. **44**: 265–275.

Murage, P.M. 1984. Potassium as a limiting nutrient for maximum production of wheat in Manitoba. M.Sc. thesis, University of Manitoba, Winnipeg, MB. 164 pp.

Murashkina, M.A., Southard, R.J., and Pettygrove, G.S. 2007. Potassium fixation in San Joaquin Valley soils derived from granitic and nongranitic alluvium. Soil Sci. Soc. Am. J. **71**: 125.

Murrell, T.S. 2018. Highlights of the frontiers of potassium science conference. [Online] Available: http://potassium.ipni.net/article/KPG-3051 [22 Nov. 2018].

Nkebiwe, P.M., Weinmann, M., Bar-Tal, A., and Müller, T. 2016. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. F. Crop. Res. **196**: 389–401.

Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). 2017. Agronomy guide for field crops. [Online] Available: http://www.omafra.gov.on.ca/english/crops/pub811/pub811.pdf [8 May 2019].

Parvej, M.R., Slaton, N.A., Purcell, L.C., and Roberts, T.L. 2015. Potassium fertility effects yield components and seed potassium concentration of determinate and indeterminate soybean. Agron. J. **107**: 943–950.

Parvej, M.R., Slaton, N.A., Fryer, M.S., Roberts, T.L. and Purcell, L.C. 2016a. Postseason Diagnosis of potassium deficiency in soybean using seed potassium concentration. Soil Sci. Soc. Am. J. **80**: 1231-1243.

Parvej, M.R., Slaton, N.A., Purcell, L.C., and Roberts, T.L. 2016b. Soybean yield components and seed potassium concentration responses among nodes to potassium fertility. Agron. J. **108**: 854–863.

Parvej, M.R., Slaton, N.A., Purcell, L.C., and Roberts, T.L. 2016c. Critical trifoliate leaf and petiole potassium concentrations during the reproductive stages of soybean. Agron. J. **108**: 2502-2518.

Saskatchewan Agriculture. 1988. Potassium Fertilization in Crop Production.

Sharpley, A.N. 1989. Relationship between soil potassium forms and mineralogy. Soil Sci. Soc. Am. J. **52**: 1023–1028.

Simonsson, M., Andersson, S., Andrist-rangel, Y., Hillier, S., Mattsson, L., and Öborn, I. 2007. Potassium release and fixation as a function of fertilizer application rate and soil parent material. Geoderma **140**: 188–198.

Slaton, N.A., Golden, B.R., DeLong, R.E., and Mozaffari, M. 2010. Correlation and calibration of soil potassium availability with soybean yield and trifoliolate potassium. Soil Sci. Soc. Am. J. **74**: 1642–1651.

Snyder, C., and Ashlock, L.O. 1996. Late-season potassium deficiency symptoms in southern soybeans. Better Crop. **80**: 10–11.

Song, S.K., and Huang, P.M. 1988. Dynamics of potassium release from potassium-bearing minerals as influenced by oxalic and citric acids. Soil Sci. Soc. Am. J. **52**: 383–390.

Walley, F.L., and Soper, R.J. 1985. Project 208: Fertilizer technology in special crop production. AGRO-MAN Research Project Report. University of Manitoba, Winnipeg, MB.

Soy Canada. 2019. Canadian Soybean Industry. [Online] Available: https://soycanada.ca/statistics/at-a-glance/ [15 Mar. 2019].

Sparks, D.L., and Huang, P.M. 1985. Physical chemistry of soil potassium. Pages 201–276 *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI.

Stammer, A.J., and Mallarino, A.P. 2018. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean. Soil Sci. Soc. Am. J. **82**: 260–270.

Statistics Canada 2018. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. [Online] Available: http://www5.statcan.gc.ca/cansim/a47 [12 Jan 2018].

Statistics Canada. 2019. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210035901 [24 April 2019].

Stewart, J.A. 1985. Potassium sources, use, and potential. Pages 83-98 *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI.

Usherwood, N.R. 1985. The role of potassium in crop quality. Pages 489–513 *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA.

Yin, X., and Vyn, T.J. 2002. Soybean responses to potassium placement and tillage alternatives following no-till. Agron. J. **94**: 1367–1374.

Yin, X., and Vyn, T.J. 2004. Critical leaf potassium concentrations for yield and seed quality of conservation-till soybean. Soil Sci. Soc. Am. J. **68**: 1626–1634.

2. SOYBEAN RESPONSE TO POTASSIUM FERTILIZER RATE AND PLACEMENT IN MANITOBA: SMALL PLOT TRIALS

2.1 Abstract

Intensively managed small plot trials were established in commercial fields in 2017 and 2018 to investigate the effectiveness of K fertilizer rates and placements for increasing soybean [*Glycine max* (L.) Merr] seed yield. Five of seven site-years had spring background ammonium acetate exchangeable soil test K (STK) values <100 mg kg^{-1}, the current threshold for recommending an application of K fertilizer for soybeans in Manitoba (MB). Six combinations of spring applied potassium chloride (KCl) rates and placements were used: 0 kg K_2O ha^{-1} (control), 33 and 66 kg K_2O ha^{-1} sidebanded and 33, 66 and 132 kg K_2O ha^{-1} broadcast and incorporated. Within each site-year, spring STK concentrations at 0-15 cm and 15-30 cm depths from each control plot at planting were highly variable within site-years. Samples were analyzed on moist soils (MK) as well on air-dried soils (DK). Soil test K concentrations in dry soil samples were significantly lower than those in moist soil samples ($P<0.05$). Potassium fertilization significantly increased tissue K concentration for two of seven site-years. Generally, a higher rate had a greater influence than placement on increasing K concentration of the whole plant (WP), stem and uppermost mature trifoliate (UMT) leaf tissue. This trend was the same for seed K concentration, with the highest rate for each placement having significantly greater seed K concentration than the control. Oil and protein content of the seed were not affected by K fertilizer treatment. No seed yield response was found for any K fertilizer treatment in any site-year. This was not anticipated based on the low concentrations of background STK at the majority of site-years. This lack of response suggests STK may not work well to indicate K responsiveness for soybeans grown in Manitoba and/or the current STK threshold of 100 mg kg^{-1} for recommending K fertilization for soybean may be too high.

2.2 Introduction

In recent years, soybean production has greatly expanded in Manitoba (MB). Soybean removes a large amount of K_2O in the seed at harvest (18 g K_2O kg^{-1} – 23 g K_2O kg^{-1} or 1.1 – 1.4 lb K_2O bu^{-1}) (Kaiser 2017, Manitoba Agriculture 2007), more than most other field crops grown in the province. The expansion of soybean acreage and soybean's high rate of K removal has contributed to a substantial increase in the total amount of K_2O removed by crops provincially, on an annual basis (Fig 2.1).

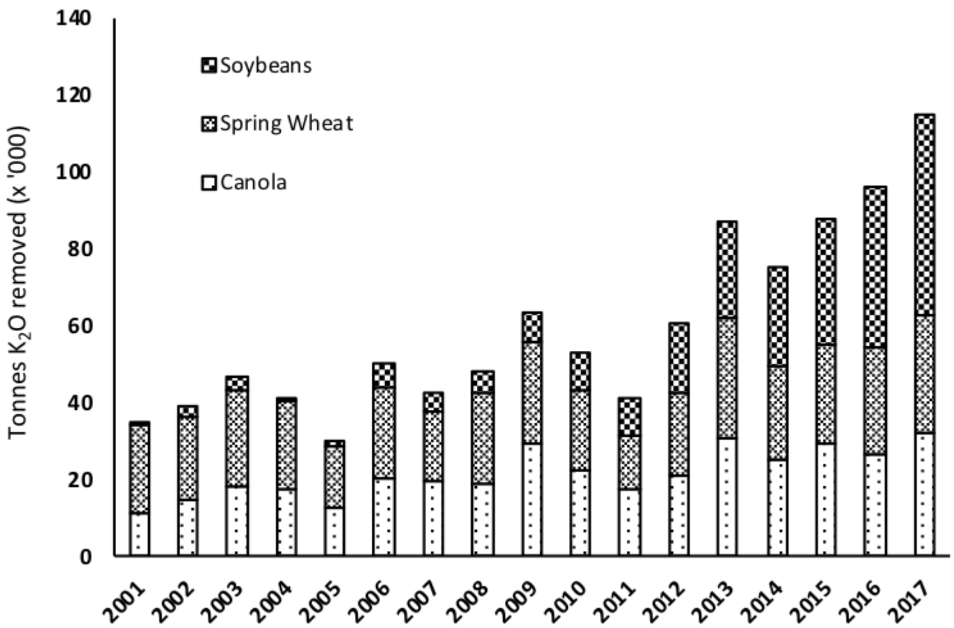

Figure 2.1 Change in cumulative province-wide annual K_2O removal for three major Manitoban crops (Statistics Canada 2018)

Traditionally, in most areas of the province, K fertility would not have been a major focus as most of MB's soils are inherently high in K. However, as soybean production has continued to expand into areas of the province dominated by coarse textured soils inherently low in exchangeable K, an increase in soybean K deficiency symptoms has been observed.

The current recommendations for K fertility of soybean in MB are based on very limited historical research, as discussed in Chapter 1. Current recommendations for K fertilization are based on an ammonium acetate exchangeable soil test K (STK) threshold of 100 mg kg^{-1} (Manitoba Agriculture 2007). If STK concentrations are between 50 and 100 mg kg^{-1}, a broadcast and incorporated application of 33 kg K_2O ha^{-1} is recommended. If STK is below 25 mg kg^{-1}, the recommendation is to apply 66 kg K_2O ha^{-1}, broadcast and incorporated. These recommendations for soybean production are identical to those for spring wheat and canola, which do not remove K at as high a rate as soybeans. In addition, the current thresholds and rates recommended for Manitoba soybean production are lower than those in neighbouring soybean producing areas such as Minnesota, North Dakota and Ontario.

The issue of fertilizer placement is of particular importance when considering a nutrient such as K, which moves via diffusion in the soil. Banding increases K availability by concentrating the fertilizer in a nutrient-dense zone that limits fertilizer-soil interaction (Nkebiwe et al. 2016). Greater root proliferation around the fertilizer rich zone may improve plant acquisition and uptake of K (Bell et al. 2009). Evaluating the efficacy of banded versus broadcast applications of K fertilizer also warrants consideration of soil properties pertaining to K availability. Bell et al. (2009) found K placement in a band may have more benefits for plant access and uptake of the fertilizer K in soils with a high K buffering capacity compared to soils with a low K buffering capacity. A MB study from the 1980s, investigating K fertility and fertilizer response of wheat, found banding K fertilizer with the seed was much more effective than broadcasting K for increasing seed early season dry matter yield, seed yield, and fertilizer use efficiency (Murage 1984). A more recent soybean study out of Iowa found only a small and infrequent yield benefit to banded K fertilizer when placed in a 10-15 cm deep band and compared with broadcast placement (Borges et al. 2003). Borges et al. (2003) attributed this lack of yield difference between band and broadcast placement to initially high STK concentrations and a lack of yield response to K fertilizer at most sites. However, they found increases in K uptake with banded compared to broadcast K application, as Murage (1984) did. This suggests banding is a more optimal placement for positional K availability and uptake, and perhaps under environmental conditions where yield potential is maximized, there may be a yield benefit to banded versus broadcast placement.

In MB, the ammonium acetate (NH_4OAc) extraction, which measures exchangeable and solution K, is the recommended soil test to determine K fertility status and fertilizer needs. Traditionally, the methodology uses an air dried and ground soil sample; however, there is debate surrounding the relevance of the exchangeable K value determined on an air-dried soil sample compared to that determined on a field moist soil sample. The concentration of exchangeable K in the soil, cation exchange capacity, mineralogy and soil organic matter affect the outcome of the drying effect on exchangeable K (Rakkar et al. 2016). In some instances, sample drying increases NH_4OAc extractable K compared to field moist soils (Barbagelata and Mallarino 2012; Breker 2017), but drying can also decrease exchangeable K. In Iowa studies, exchangeable K determined on a field moist sample was better correlated to yield than when determined on a dry sample (Barbagelata and Mallarino 2012). Conversely, research in North Dakota found the standard NH_4OAc extraction on an air dried soil was best correlated to corn yield response (Breker et al. 2019) when compared with NH_4OAc extraction on a moist soil and extraction methods that include a portion of the nonexchangeable K pool.

In addition to the standard NH_4OAc extraction to quantify exchangeable K, there is interest in the use of ion exchange resins, such as Western Ag Innovations Plant Root Simulator

(PRS®) probes, to quantify bioavailable K. Use of PRS® technology allows for measurement of a soil's K supply rate, which is the amount of K adsorbed to the exchange resin over the burial period duration, either in laboratory or field settings. The quantity of nutrients measured by an ion exchange resin in the soil will depend on soil moisture and temperature, as well as biotic and abiotic competition (Qian and Schoenau 2002). This method of soil testing is of particular interest and relevance for ions that move via diffusion in the soil, such as K, which may be affected more by such conditions compared with nutrients that move predominantly by mass flow.

Tissue K concentration can be used as an indicator of soybean K nutrition status at various points in the growing season. Although midseason K applications are unlikely to correct a deficiency in that growing season, tissue K concentration data are valuable to evaluate the efficacy of a current K fertilizer program, and whether modifications are required in the future to ensure adequate K fertility. Critical tissue K concentration ranges are typically established for whole plants (WP) at V5-6 growth stage (Clover and Mallarino 2013; Stammer and Mallarino 2018) and uppermost mature trifoliate (UMT) leaves at R2-3 (Clover and Mallarino 2013; Parvej et al. 2016a; Stammer and Mallarino 2018). Soybean yield response to K fertilizer is better correlated with trifoliate-leaf K concentration at early reproductive stages than WP concentration at V5-6 vegetative stage (Clover and Mallarino 2013; Stammer and Mallarino 2018). Additionally, K concentration in soybean tissue is more responsive to K fertilization than dry matter yield of young vegetative tissue, seed yield and K concentration of the seed (Fernández et al. 2009; Clover and Mallarino 2013).

In addition to tissue concentration responses, K fertility impacts soybean seed yield, seed K concentration, oil and protein content. Soybean seed yield response to K fertilization is variable. In Iowa, for corn and soybean, Clover and Mallarino (2013) found between 30 and 45% of sites had yield responses to K fertilization in the low, optimum and high classes of background STK. The only STK category where they did not see a yield response to K fertilization was very high, >181 mg K kg^{-1}. Canadian research investigating soybean yield response to K fertilization on medium and high testing soils has suggested responsiveness is not strongly related to background STK concentrations (Yin and Vyn 2002), exemplifying the variability in soybean yield response to K fertilization. Parvej et al. (2015) found a 13 to 15% yield decline for soybean grown on low K soil (61 to 67 mg Mehlich-3 extractable K kg^{-1}) compared with those on medium to high K soil (with Mehlich-3 soil test K concentrations up to 91 mg K kg^{-1}). They partitioned yield components of the soybeans grown under long term low, medium and high K fertility and found soybeans grown in low K fertility soils had yield loss which was attributed to fewer pods and seeds, increased seed abortion and smaller seeds. Where yield decline as a result of inadequate K fertility is found, these would be the expected mechanisms of yield loss.

Just as K concentration of soybean tissue is affected, K concentration of the seed is also affected by K fertility and fertilization. However, seed K responses are not always consistent with increases in K fertility (Clover and Mallarino 2013; Parvej et al. 2015). Usherwood (1985) reported that increases in K fertility from low to very high resulted in absolute increases in seed K concentration of 0.84%. While numerically not very large, such increases can raise the K nutrition status of soybean above critical levels, reducing the threat of deficiency. Parvej et al. (2015) found increases in seed K concentration with increases in K fertility level of the soil, from an average of 15.8 g K kg^{-1} in low K fertility treatments to 19.8 g K kg^{-1} in high K fertility treatments. However, in the same study, increases in seed K concentration as a result of K fertilization did not necessarily correspond with seed yield increases (Parvej et al. 2015).

Potassium fertility and fertilizer practices can also influence oil and protein content of the soybean seed (Usherwood 1985). However, Krueger et al. (2013) and Farmaha and Nafziger (2012) did not find a significant change in oil or protein concentration as a result of K fertilization. Haq and Mallarino (2005) reported inconsistent differences in oil and protein content of soybean seed resulting from different K fertilization practices. Oil content increased at some sites in response to K fertilization, but decreased at others, with both broadcast and banded K fertilizer resulting in oil content increases in some cases. Potassium fertilizer effect on grain protein content was also inconsistent, with both increases and decreases relative to the control. The relationship between grain yield and oil and protein content was non-significant, likely explained by the immense influence of environmental conditions on seed quality parameters.

Evidently, soybean response to K fertility and fertilizer is complex, with numerous interacting factors determining the response in tissue K, seed yield, seed K, oil and protein content. Given the expansion of soybean production and the lack of comprehensive historical research for K fertility of soybean in MB, as well as the large K removal of soybean, there is merit to investigating the effects of K fertility and fertilizer on soybean production. The main objective of this study was to investigate the effectiveness of different K fertilizer rates and placements to increase soybean seed yield. Tissue K, seed K, oil, and protein concentration responses were also investigated. We hypothesized that higher rates of K fertilizer would increase soybean K response and banded placement would be more effective at increasing soybean K uptake and seed yield than broadcast placement.

2.3 Materials and Methods

2.3.1 Site Selection and Description

Sites were selected for topographic uniformity and low STK (ideally <100 mg kg^{-1} determined on a dried and ground soil). Potential sites were visually assessed, and 16-20 soil cores from 0-15 cm depth were collected, in the spring, in a zig-zag pattern across the entire site area. A uniform composite sample from each potential site was sent to Agvise Laboratories (Northwood, ND) for complete fertility analysis after air-drying, including extraction and analysis for exchangeable K using 1 M NH_4OAc (pH 7.0) extracting solution at a 1:10 soil to solution ratio which was analyzed with a Perkin Elmer 5400 ICP-OES. Details for soil sampling and STK analyses for sites that were selected and used for the small plot study are presented in Section 2.3.4.

Four sites were selected in 2017, near Elm Creek, MB (49˚37’55” N, 97˚59’19” W), Haywood, MB (49˚36’35” N, 98˚9’33” W), St. Claude, MB (49˚34’21’ N, 98˚19’05” W) and Portage la Prairie, MB (49˚48’33” N, 98˚23’53” W). Three sites were selected in 2018, near Haywood, MB (49˚41’00” N, 98˚12’17” W), Long Plain, MB (49˚50’46” N, 98˚25’13” W) and Bagot, MB (49˚56’57” N, 98˚33’17” W). All of these sites were located in commercial fields. The complete analysis from the site characterization soil sample was used to determine background fertility plans for each site. This included applications of sulphur (S), phosphorus (P) and micronutrients such as copper (Cu) and zinc (Zn) (Appendix I). According to current soil test thresholds in the Manitoba Soil Fertility Guide (Manitoba Agriculture 2007) five of the seven site-years are classified as low in K for soybean production and the other two site-years were marginally sufficient (Table 2.1).

Table 2.1 Spring pre-planting soil nutrients for each site-year

Site-Year	Soil Test Values[a]				
	K	N	P	S	pH
Elm Creek 2017	101	12	13	22	7.1
Haywood 2017	61	12	7	40	8.3
St. Claude 2017	96	15	6	90	8.6
Portage la Prairie 2017	62	8	19	18	6.9
Haywood 2018	117	11	18	11	5.8
Long Plain 2018	95	13	40	9	5.0
Bagot 2018	49	43	4	40	8.0

[a] 0-15 cm ammonium acetate exchangeable K (mg kg^{-1}), nitrate-N (kg ha^{-1}), Olsen extractable P (mg kg^{-1}), and sulphate-S (kg ha^{-1})

2.3.2 Experimental Design and Treatments

The experiment was set up as a randomized complete block design, with four replications. There were six treatments at each location, including a control with no added K, two sidebanded treatments with 33 or 66 kg K_2O ha^{-1}, and three broadcast and incorporated treatments with 33, 66, or 132 kg K_2O ha^{-1}. The 33 and 66 kg K_2O ha^{-1} rates were selected to reflect rates currently recommended in the Manitoba Soil Fertility Guide. The 132 kg K_2O ha^{-1} rate was included to investigate whether a higher rate is necessary for K response at broadcast and incorporated placement, due to potential reduced efficiency compared to sidebanded placement. All fertilizer K was applied in the form of potassium chloride (potash, KCl, 0-0-60). Sidebanded treatments were banded through the planter and placed 5 cm beside and 5 cm below the seedrow. Broadcast and incorporated treatments were broadcast by hand and subsequently incorporated with a double tillage pass with a tandem disc, prior to planting. As part of the background fertility plan, phosphorus was applied as monoammonium phosphate (MAP, 11-52-0) through the planter, placed in the sideband, for each site-year. For each site in 2017, a sulphur, copper and zinc blend was applied through a Gandy Box push spreader as ammonium sulphate (AS, 21-0-0-24), copper sulphate and zinc sulphate, and incorporated with two tillage passes with a tandem disc prior to planting. For each site in 2018, AS was hand broadcast in season. At the 2018 Haywood site, nitrogen fertilizer was applied as a rescue treatment at the R2 growth stage in response to a nodulation failure. At this site-year only, Agrotain® treated urea was broadcasted at a rate of 112 kg N ha^{-1}.

Roundup Ready II soybean variety DKB005-52 was planted to achieve a target plant stand of 370 500 plants ha^{-1}. Planting depth ranged from 0.64 to 1.3 cm, depending on soil moisture conditions at each site-year. A John Deere 1755 4-row precision planter was used, with the rows on 76 cm spacing. The seed was treated with Acceleron® seed treatment, which contained Imidacloprid insecticide, Fluxapyroxad, Pyraclostrobin and Metalaxyl fungicides. The seed was also treated with Optimize® ST liquid inoculant. In addition to the inoculant on the seed, Cell-Tech™ liquid inoculant was applied in the seedrow through the liquid kit on the planter at a rate of approximately 190 L ha^{-1}. Each plot was 3 m x 8 m. Planting was targeted for the middle of May (Table 2.2). Glyphosate was applied in-crop at a rate of 1.65 L ha^{-1} with a bike sprayer or tractor sprayer on an as-needed basis to manage the weed population throughout the season (Appendix I).

Table 2.2 Planting and harvest dates for 2017 and 2018 small plot trials

Site-Year	Planting Date	Harvest Date
Elm Creek 2017	May 19, 2017	Oct. 5, 2017
Haywood 2017	May 19, 2017	Sept. 30, 2017
St. Claude 2017	May 19, 2017	Sept. 29, 2017
Portage la Prairie 2017	May 18, 2017	Oct. 29, 2017
Haywood 2018	May 17, 2018	Oct. 18, 2018
Long Plain 2018	May 17, 2018	Oct. 18, 2018
Bagot 2018	May 17, 2018	Oct. 19, 2019

2.3.3 Weather Conditions

The DKB005-52 soybean variety used in this study has a corn heat unit (CHU) requirement of 2425, which was met according to the accumulated CHU measured at the weather stations nearest each site-year (Table 2.3). Both 2017 and 2018 growing seasons were characterized by drier than normal conditions (Table 2.4). To maximize yield potential, soybeans require more than 400 mm of water (Licht et al. 2013). Since normal growing season precipitation is less than 400 mm for the regions where the site-years were located, the yield limiting effect of moisture stress is a concern in these areas, even if normal precipitation occurred. Although total growing season precipitation is important, the distribution of that precipitation throughout the growing season is also informative to investigate potential yield limiting effects of moisture stress, particularly growing season precipitation during the period of maximum water and nutrient uptake. For soybean, the majority of water and nutrient uptake occurs between the R1 and R5 growth stages [Manitoba Pulse and Soybean (MPSG) 2018], which typically extends from early July to mid-late August. By the end of August in 2017 the site-years had received between 48 and 57% of normal growing season precipitation (Table 2.5). By the end of August 2018, the site-years had received between 63 and 69% of normal precipitation. So, total growing season precipitation was less than the required amount to achieve maximum soybean yield potential and the quantity of precipitation during the time of maximum water uptake was less than normal. Thus, lack of moisture was a yield limiting factor during the 2017 and 2018 growing seasons and the effect of this moisture stress was probably exacerbated by the coarse textured soils at the site-years.

Table 2.3 Average air temperature, total corn heat units (CHU), monthly and total precipitation for weather stations in close proximity to small plot site-years

Weather Station[a] (growing season)	Average Air Temperature[b]	Precipitation							
		CHU_{Total}[b]	May	June	July	Aug	Sept	Total to end of: Aug	Sept
	–°C –		– mm –					– mm –	
Elm Creek (2017)	16.9	2637	15.9	70.2	23.3	13.7	100.5	123.1	223.6
Portage (2017)	15.3	2713	9.5	63.2	52.9	15.4	69.0	141.0	210.0
Elm Creek (2018)	16.3	2761	29.1	70.1	40.8	22.3	65.2	162.3	227.5
Portage (2018)	15.8	2709	20.6	92.9	36.9	20.1	124.7	170.5	295.2

[a]Manitoba Agriculture's Elm Creek and Portage weather stations were the closest to our field sites; data was downloaded from the Manitoba Agriculture Daily Weather Report (https://web43.gov.mb.ca/climate/DailyReport.aspx)
[b]Average air temperature and total CHU are from May 19 – Oct 5 for Elm Creek (2017), May 18 – Oct 8 for Portage (2017), May 17 – Oct 18 for Elm Creek (2018) and May 17 – Oct 19 for Portage (2018)

Table 2.4 Growing season precipitation normal and actuals, to the end of September

Weather Station	Normal Precipitation	Year	Actual Precipitation	Percent of Normal Precipitation
	– mm –		– mm –	
Elm Creek	345	2017	223.6	65%
		2018	227.5	66%
Portage	335	2017	210	63%
		2018	295.2	88%

Table 2.5 Growing season precipitation normal and actuals, to the end of August				
Weather Station	Normal Precipitation	Year	Actual Precipitation	Percent of Normal Precipitation
	——— mm ———		——— mm ———	
Elm Creek	257	2017	123.1	48%
		2018	162.3	63%
Portage	246	2017	141	57%
		2018	170.5	69%

2.3.4 Soil Measurements

For sites that were selected for the small plot trials, soil samples were collected from each replicate of the control treatment within a week after planting (for a total of 4 composite samples per location) to characterize STK on a moist soil (MK) and a dry soil (DK) basis. Ten soil cores per control plot were taken at 0-15 cm and 15-30 cm depths, five cores from each planter wheel track. Cores were intentionally taken from the wheel tracks to increase accuracy of sampling depth, as this soil was compressed from the planting operation. Cores were put into plastic bags to make a composite sample for each depth for each control plot. These samples were stored in a walk-in cooler at 4˚C until sample processing.

To homogenize the soil samples, each composite sample was mixed thoroughly in the bag. Once mixed, two subsamples of each soil (~ 20 g in each subsample) were used to determine soil moisture content on an air-dry and oven-dry basis. The remainder of the composite sample was split in two equal portions. Half was resealed in the plastic bag and placed back in the walk-in cooler until processing for MK determination. The other half was spread on kraft paper and placed on trays to dry at room temperature for 48 hours. These samples were then ground with a high-speed pulveriser soil grinder, to mimic typical commercial soil test lab practice for air-dried soil samples.

Ammonium acetate exchangeable soil test K was determined using the Pratt (1965) method, with an addendum for MK determination; also, solution K was included in the quantification of exchangeable K. Dry soil K was determined using the air-dried and ground samples. Five grams of dry soil were weighed into 50 mL centrifuge tubes. Twenty-five mL of neutral 1 M NH_4OAc extraction solution were added and shaken for 5 minutes on a reciprocating shaker at 150 strokes per minute. Samples were then filtered through Whatman No.1 filter paper, collected in scintillation vials and analyzed by Farmer's Edge Laboratories (Winnipeg, MB) for K, Ca, Mg and Na using a Thermo Scientific iCAP Spectrometer. Moist soil K was determined on the same basis, but with a modification for the amount of soil used in the extraction. The quantity of soil used in the moist extraction was based on the soil moisture content determined on an air-dry basis during soil processing, using the following equation:

$$5\text{ g} + (5 \times \%\text{ soil moisture content}/100)$$

The rest of the procedure was the same as for DK determination.

Potassium supply rates were measured at three times throughout the field season using Plant Root Simulator® (PRS) probes from Western Ag Innovations. Four cation and anion probe pairs were buried approximately 10 cm deep in each control plot and each 132 kg K_2O ha^{-1} plot at each site-year for a duration of two weeks. To insert the probes, a slot was made in the soil with a knife 10-15 cm adjacent to the seed row. One cation and one anion probe were inserted adjacent to each other. A back-cut was made using the knife, pressing the soil against the probe to ensure adequate soil-probe contact. The soil around the probe was then compressed with a boot heel. Probes were first buried two weeks after planting, to assess early season K diffusion with little or no plant root influence, then at the V4-V6 stage to assess K diffusion during maximum vegetative growth, and lastly at R4-5 to assess the K availability and dynamics during the period of the maximum rate of nutrient and water uptake. At the end of each burial period, probes were removed, thoroughly cleaned with deionized water and sent to Western Ag Innovations for analysis. Potassium supply rates were reported as micrograms/10 cm^2/two weeks.

2.3.5 Tissue Measurements

Tissue samples were collected to determine soybean K uptake as well as K concentration of tissue components. Two tissue sample timings were targeted: an early season timing, at V5-V6 to determine K concentration of the whole plant and K uptake, and a late season timing at R2 to determine K concentration in the UMT leaves and stem portions. However, at all site years these two growth stages coincided. As a result, for each site-year, all three types of tissue were collected at one sample timing (i.e., the soybeans were at V5-6/R2 when all samples were collected).

To determine K uptake, 10 whole plants per plot were cut at the soil surface. Samples were collected from only the middle two rows of each plot. Samples were stored in mesh bags, and air dried for at least 48 hours to reduce moisture content. Following air-drying, samples were oven-dried in a forced air oven for at least 24 hours at 60˚C. The oven-dry mass was taken and then samples were ground to pass through a 2 mm sieve using a Wiley Mill grinder. Samples were sent to Agvise Laboratories (Northwood, ND) for K analysis by digestion with a nitric acid/hydrogen peroxide cook down method, and then analyzed for K content with a Perkin Elmer 5400 ICP-OES.

Uppermost mature trifoliate leaves and stem portions were also collected to determine tissue K concentration. Twenty-five UMT leaves, including the three leaflets and petiole, were collected from the centre two rows of each plot. At the same time, the portion of stem from node to node directly above the trifoliate sampled was collected using small garden shears. The UMT samples and stem samples were both air-dried for at least 48 hours to reduce moisture content, and then oven-dried in a forced air oven at 60˚C for at least 24 hours. Once dry, the samples were ground to pass through a 2 mm sieve using a Wiley Mill grinder. Samples were sent to Agvise Laboratories (Northwood, ND) for K analysis by digestion with a nitric acid/hydrogen peroxide cook down method, and then analyzed for K content with a Perkin Elmer 5400 ICP-OES.

2.3.6 End of season Measurements

At maturity, the two centre 8 m length rows from each plot were harvested using a plot combine (Wintersteiger Classic). The combine's HarvestMaster® Classic GrainGage system was used to determine yield and moisture content. A subsample of seed was collected from each plot to determine oil and protein content and seed K concentration. The seed subsamples were divided in half, with half being sent to the Agriculture and Agri-Food Canada station in Morden, Manitoba for oil and protein analysis via NIR using a FOSS Infract 1241 Grain Analyzer. The other half of the seed samples were dried in a forced air oven at 60˚C for at least 24 hours. Once dry, the samples were ground in a coffee grinder for approximately 10 seconds per sample. Ground samples were sent to Agvise Laboratories (Northwood, ND) for seed K determination by digestion with a nitric acid/hydrogen peroxide cook down method, and then analyzed for K content with a Perkin Elmer 5400 ICP-OES.

2.3.7 Statistical Analysis

Analysis of variance (ANOVA) was conducted using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc 2018). Site-year and treatment were fixed effects, while block (site-year) was a random effect. Site-year was treated as a fixed effect, so that we could investigate site-year x treatment interactions and assess the effect of site-year conditions (e.g., soil test K concentration) on response to K fertilization. Assumptions of normality of the data were tested using Proc Univariate, with the data assumed to follow a normal distribution if the Shapiro-Wilk statistic was >0.90. Unequal variances with sites that may have had missing data were corrected for in the GLIMMIX procedure using the Satterthwaite approximation. Letter groupings were assigned to least square means (P<0.05) using the Tukey-Kramer test. Ammonium acetate STK in the control plots at planting and seed protein content followed a log normal distribution, accounted for in the GLIMMIX procedure using the DIST=lognormal function. After analysis, data were back-transformed to be reported in their original units. Plant Root Simulator® probe K supply rates also did not follow a normal distribution, so a gamma distribution and appropriate back transformation were performed in GLIMMIX, using the DIST=gamma and ilink functions, respectively. For data where regression analysis was utilized, Proc Reg was used to determine the relationships and test for significance, using an F test threshold of P<0.05. The ammonium acetate STK dataset, which was not normally distributed, was transformed in Excel to log log values and regression was performed on the transformed data.

2.4 Results and Discussion

2.4.1 Ammonium Acetate Exchangeable Potassium at Planting

Ammonium acetate exchangeable K at planting was highly variable within site-years, indicating STK in the top 30 cm is spatially variable at a small scale across a field. Analysis of variance indicated a significant effect of soil sample drying on STK value (Table 2.6), meaning STK was significantly different depending on the method for handling the soil sample. Overall, MK was greater than DK, and this effect was consistent across site-years and depths. Although the effect of sampling depth was not significant alone, the effect of soil sample depth on STK values varied from one site-year to another, as indicated by the significant site-year x depth interaction (Table 2.6). At Haywood 2017 and St. Claude 2017, STK in the 15-30 cm depth was significantly greater than in the 0-15 cm depth (Table 2.7). At Haywood 2018 and Long Plain 2018, the opposite was true, with the 0-15 cm depth having significantly greater STK than the 15-30 cm depth. At the other three site-years, differences in STK values between the two depths were not significantly different. Differences in STK between the two depths could be related to soil types, fertilizer, and management history at each location. A study in North Dakota also assessed DK and MK for both 0-15 and 15-30 cm soil sampling depths. They found numerically less STK in the second depth at each of the three study locations, but found a larger percent change in the value of MK compared with DK at this deeper depth (Rakkar et al. 2016). Given the lack of significant depth x sample preparation interaction in our study, there was no indication in this dataset that differences in moist and dry STK varied with sample depth.

Table 2.6 Effect of soil sample drying on ammonium acetate exchangeable K (STK) at planting		
		STK[a]
		—— mg kg^{-1} ——
Sample Preparation		
Dry soil basis		60*b*
Moist soil basis		74*a*
ANOVA	df	*Pr>F*
Sample Preparation	1	0.007*
Site-year	6	0.0102*
Site-year*Preparation	6	0.3052
Depth	1	0.5407
Preparation*Depth	1	0.2642
Site-year*Depth	6	0.0001*
Site-year*Preparation*Depth	6	0.6082
Coeff Var (C.V.)		69

*Significant at P<0.05
[a]Means followed by the same letter are not significantly different (P<0.05)

Table 2.7 Ammonium acetate exchangeable soil test K (STK) for 0-15 and 15-30 cm depth in control plots at planting for each site-year		
Site-year	Depth[a]	
	0-15 cm	15-30 cm
	—— mg kg^{-1} ——	
Elm Creek 2017	80*a*	96*a*
Haywood 2017	42*b*	69*a*
St. Claude 2017	57*b*	118*a*
Portage la Prairie 2017	55*a*	56*a*
Haywood 2018	101*a*	68*b*
Long Plain 2018	106*a*	69*b*
Bagot 2018	49*a*	36*a*

[a]Means within rows that are followed by the same letter are not significantly different (P<0.05)

Regression analysis indicated a significant relationship (P<0.05) between DK and MK at both 0-15 cm (P = <0.0001) and 15-30 cm (P = <0.0001) depths (Fig 2.2). The slope coefficient relating MK to DK for the 0-15 cm depth is less than 1, which indicates that increases in STK analyzed on a moist soil were generally smaller than increases in STK determined on a dry soil. This is consistent with the findings of Breker (2017) who determined increases in MK were generally less than increases in DK for several North Dakota soils. However, the regression has a positive Y intercept, which indicates that MK values could be more likely to be greater than DK values at low concentrations of DK. Contrary to the nature of the relationship between MK and DK for the top 15 cm of soil, the slope coefficient relating MK and DK at the 15-30 cm depth was greater than one, meaning increases in MK were usually greater than increases in DK (Fig 2.3). Again, however, the Y intercept from the regression equation shows the opposite trend; at low MK concentrations, there is a tendency for DK to become greater than MK. The inconsistency in the DK vs. MK relationship at differing soil depths and concentrations of background STK indicates the highly variable nature of K in soils. The factors dictating the amount of exchangeable K measured with NH_4OAc are not limited to the physical processing of the soil samples, but also include the amount of K present.

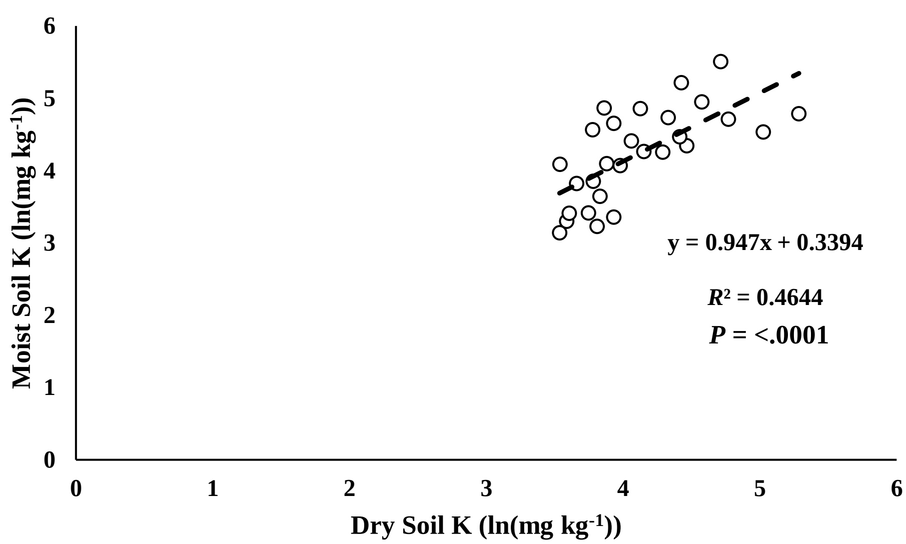

Figure 2.2 Relationship between the natural log (ln) of NH_4OAc exchangeable soil test K measured on air-dried soil samples (Dry K) and the natural log of NH_4OAc exchangeable soil test K measured on moist soils (Moist K) for 0-15 cm soil depth

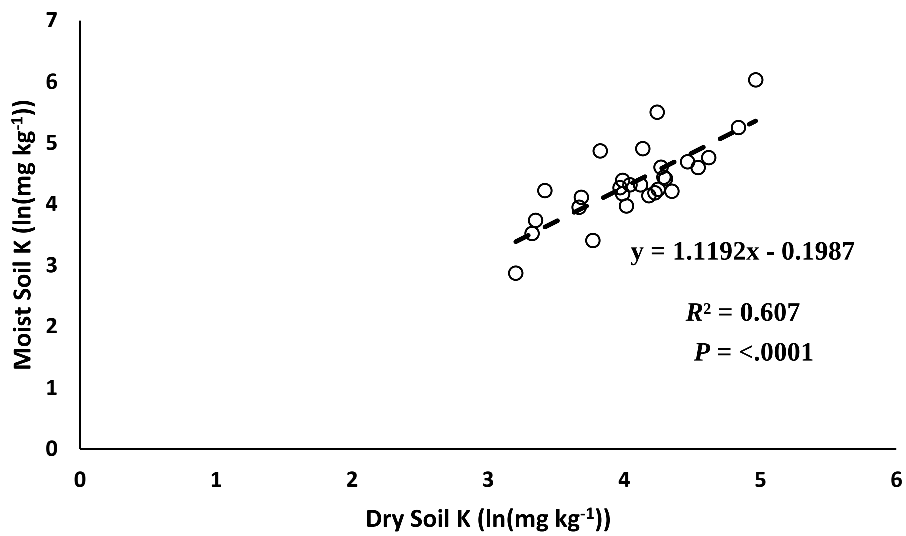

Figure 2.3 Relationship between natural log (ln) of NH_4OAc exchangeable soil test K measured on air-dried soil samples (Dry K) and the natural log of NH_4OAc exchangeable soil test K measured moist soils (Moist K) for 15-30 cm soil depth

Our study's finding that, overall, MK is significantly greater than DK contrasts with other results in the literature. Barbagelata and Mallarino (2012) found STK to be an average of 1.92 times greater when determined on dry soil samples compared to moist soil samples. Similarly, Breker (2017) found DK to be an average of 1.27 times greater than MK. The difference in relationship of DK and MK between these two studies and the results presented here cannot be attributed to sample preparation and analytical methodology, as similar procedures were followed in all three studies. However, there could be mineralogical differences that are affecting the outcome of the physical processes of drying; perhaps more mineral dehydration and collapse of interlayer space is occurring in these MB soils with drying, whereas in the Barbagelata and Mallarino (2012) and Breker (2017) studies, more scrolling of mineral layers and subsequent K release could have resulted from the drying process. Interlayer dehydration and collapse lead to trapping or fixation of K in the interlayer space (Barbagelata and Mallarino 2012) and thus a decline in measurable NH_4OAc exchangeable K, as may have been the case in the MB soils. In other studies, the release of K, previously non-exchangeably trapped in the interlayer spaces, could have resulted from scrolling of mineral layers upon drying, which increases STK from a dry soil sample (Barbagelata and Mallarino 2012).

2.4.2 Plant Root Simulator (PRS®) Potassium Supply Rate

Despite substantial variability within site-years and treatments, Plant Root Simulator (PRS®) probes indicated significantly different K supply rates between treatments and between burial periods. The interaction between treatment and site-year was also significant (Table 2.8). Except at Haywood 2018, a significantly greater K supply rate was measured in the 132 kg K_2O ha^{-1} broadcast and incorporated treatment compared to the control. The magnitude of difference in K supply rates between the two treatments varied among site-years, but the increase in supply rate detected in the K fertilized treatments indicates that some of the added fertilizer K was probably accessible by the soybean roots. The K supply rates in the control plots also varied among site-years with Haywood 2017, St. Claude 2017 and Bagot 2018 having K supply rates an order of magnitude lower than the other four site-years. This indicates a difference in exchangeable and potentially bioavailable K levels among site-years, likely due to different soil types and characteristics, as well as different soil temperature and moisture, since the exchange resins are subject to the same environmental, chemical and biological conditions as plant roots (Qian and Schoenau 2002). The differences in magnitude among site-years indicate there were inherent differences in bioavailability of K, and the greater K supply found in treated plots indicates that K fertilization increased the supply of bioavailable K in most of the studied soils.

Table 2.8 Effect of burial period and K treatment on PRS® K supply rates for each site-year

Burial Period[1]	Site-Year[b]							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot
	2017	2017	2017	2017	2018	2018	2018
	——— μg K/cm²/2 weeks ———						
1	368*a*	83a*b*	103*ab*	326*a*	329*a*	322*a*	30*a*
2	253*a*	90*a*	127*a*	186*b*	299*a*	227*a*	39*a*
3	217*a*	56*b*	82*b*	157*b*	186*b*	278*a*	39*a*
Treatment[a]							
0 kg K_2O ha^{-1}	228*b*	45*b*	76*b*	122*b*	183*a*	177*b*	23*b*
132 kg K_2O ha^{-1} BI	325*a*	126*a*	137*a*	369*a*	380*a*	417*a*	54*a*

ANOVA	Df	*Pr>F*
Burial Period	2	<0.0001*
Treatment	1	<0.0001*
Site-year	6	<0.0001*
Burial*Treatment	2	0.8739
Site-year*Burial	12	0.0003*
Site-year*Treatment	6	0.0083*
Site-year*Burial*Treatment	12	0.8237
Coeff Var (C.V.)		87

*Significant at $P<0.05$

[1]Each burial period was two weeks in duration. Burial period 1 was two weeks after planting, burial period 2 was during the V4-6 growth stage and burial period 3 was during the R4-5 stage

[a] BI indicates broadcast and incorporated treatment

[b]Means within columns followed by the same letter are not significantly different ($P<0.05$)

The effect of burial period also varied with site-year, as indicated by a significant interaction for site-year x burial period (Table 2.8). Elm Creek 2017, Long Plain 2018 and Bagot 2018 did not have significant differences in K supply rates between burial periods. At Haywood 2017 and St. Claude 2017, K supply rate was numerically highest during the period of maximum vegetative growth (burial 2) and this was statistically greater than K supply rate during maximum reproductive growth (burial 3). Potassium supply rates for burial 1 and burial 2 were not significantly different at these two site-years. At Portage la Prairie 2017 the greatest K supply rate was at the beginning of the season in burial period 1. At Haywood 2018, K supply rates for burial periods 1 and 2 were statistically similar, and both were significantly greater than the K supply rate during burial period 3. The general trend, where statistical differences between burial periods were present, was a reduction in K supply rate as the season progressed. However, in the case of Haywood 2017 and St. Claude 2017, only the K supply rates for the second burial period were significantly greater than for the third. A reduction in K supply as the season progresses and soybean enters reproductive growth is not a major concern for K nutrition of the soybean crop. Recent research in Wisconsin that partitioned soybean K uptake found more than 50% of soil K uptake occurred before R3 and by R5.5 more than 90% of total K uptake was complete (Gaspar et al. 2017). A declining trend in K supply rate as the growing season progresses could be due to crop-related factors, with available K depletion occurring as uptake occurs over the season, as well as environmental factors such as reduced soil moisture due to evapotranspiration and lack of precipitation.

Given the nature of K dynamics, particularly its diffusion-mediated movement, and the knowledge that K measured with an NH_4OAc extraction may not be equivalent to the amount of K that is bioavailable throughout the soybean growing season, use of exchange resins such as the PRS® technology could provide complementary information about K fertility status of different soils. When used in-situ, the probes are useful for detecting K supply rates at different times over the growing season, which can be used to compare potential plant availability of K for these different periods. Additionally, the probes can be used to indicate whether added fertilizer K could potentially be available for plant uptake, especially given the nature of the PRS® technology when used in situ, and the fact that the probes are exposed to the same environmental, chemical and biotic conditions as plant roots.

2.4.3 Tissue Potassium Concentration and Uptake

Analysis of variance indicated a significant effect of K fertilizer treatment, as well as a site-year x treatment interaction for WP K concentration (Table 2.9), indicating treatments were not having the same effect on magnitude of WP K concentration at all site-years. Only two of the seven site-years had significant differences in WP K concentration between treatments. At Portage la Prairie 2017, all K applications, except 33 kg K_2O ha^{-1} broadcast and incorporated, had significantly higher WP K concentrations than for the control. The 132 kg K_2O ha^{-1} broadcast and incorporated treatment had the highest K concentration, which was significantly greater than for the sidebanded treatment of 66 kg K_2O ha^{-1}. At Bagot 2018, the low rate (33 kg K_2O ha^{-1}) for the sidebanded treatment and the broadcast and incorporated treatment did not result in significantly greater WP K concentrations compared to the control, but all other treatments had significantly higher K concentrations than for the control. The lack of significant differences in WP K concentration within the higher rates for both placements, and the similar K concentrations for these placements at the low rate of K, suggests rate had a greater impact on WP K concentration than placement for these site-years. Stammer and Mallarino (2018) determined that the critical K concentration range for whole plant soybean tissue at the V5-6 growth stage was 18.9 to 22.6 g kg^{-1}. According to this criterion, only the 132 kg ha^{-1} broadcast and incorporated treatment at Portage la Prairie 2017 was sufficient to raise whole plant tissue K concentration above the critical range. All other treatments in each site-year were within or below the critical range, reflecting the low K fertility of these sites and, perhaps, the dry conditions of these two growing seasons. At all site-years, growing season rainfall was below normal, with less than 60 and 70% of normal growing season precipitation to the end of August, for 2017 and 2018 respectively. Lower than normal moisture accumulation could have reduced the ability of both soil K and added fertilizer K to effectively move to plant roots via diffusion for uptake.

Table 2.9 Effect of K fertilization on whole plant K concentration for each site-year

Treatment[a]	Site-Year[b]						
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot
	2017	2017	2017	2017	2018	2018	2018
				$g\ kg^{-1}$			
0 kg K_2O ha^{-1}	19.0*a*	14.3*a*	19.5*a*	15.5*c*	15.0*a*	19.3*a*	13.0*b*
33 kg K_2O ha^{-1} SB	18.3*a*	15.5*a*	21.8*a*	18.3*bc*	16.0*a*	21.3*a*	15.0*ba*
66 kg K_2O ha^{-1} SB	19.3*a*	14.8*a*	20.0*a*	19.8*b*	16.3*a*	20.3*a*	17.5*a*
33 kg K_2O ha^{-1} BI	18.5*a*	15.5*a*	20.0*a*	20.0*b*	16.3*a*	18.3*a*	14.5*ba*
66 kg K_2O ha^{-1} BI	19.8*a*	17.0*a*	20.3*a*	21.8*ba*	15.8*a*	18.8*a*	17.3*a*
132 kg K_2O ha^{-1} BI	20.0*a*	16.3*a*	20.3*a*	25.0*a*	16.8*a*	21.8*a*	18.5*a*

ANOVA	df	*Pr>F*
Trt	5	<.0001*
Siteyr	6	<.0001*
Siteyr*Trt	30	0.0208*
Coeff Var (C.V.)		18

*Significant at $P<0.05$
[a] SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment
[b]Means within columns followed by the same letter are not significantly different ($P<0.05$)

Analysis of variance did not indicate a significant fertilizer treatment effect or site-year x fertilizer treatment interaction for WP dry matter yield (Appendix II). Additionally, analysis of variance indicated K fertilizer treatments were having a similar effect on K uptake across site-years, with no significant treatment x site-year interaction (Table 2.10). However, the only treatment that resulted in significantly greater K uptake compared to the control was 66 kg K_2O ha^{-1} sidebanded, with a 2.2 kg K ha^{-1} increase for treated soybean. All other treatments resulted in K uptake that was statistically similar to the control.

Table 2.10 Effect of K fertilization on K uptake for each site-year

Treatment[a]	Site-Year[b]							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot	All Sites
	2017	2017	2017	2017	2018	2018	2018	2017-2018
				——— kg K ha^{-1} ———				
0 kg K_2O ha^{-1}	16.8	9.3	10.7	11.6	11.1	18.5	14.5	13.2*b*
33 kg K_2O ha^{-1}SB	17.4	8.8	12.1	14.0	13.1	21.3	19.0	15.1*ba*
66 kg K_2O ha^{-1} SB	17.8	9.0	11.7	14.8	12.8	20.3	21.2	15.4*a*
33 kg K_2O ha^{-1} BI	17.7	8.3	9.7	15.1	12.9	18.1	15.6	13.9*ba*
66 kg K_2O ha^{-1} BI	17.7	10.4	11.7	16.5	10.0	17.8	18.2	14.6*ba*
132 kg K_2O ha^{-1} BI	17.0	8.7	11.4	17.0	12.0	19.6	19.9	15.1*ba*

ANOVA	df	*Pr>F*
Trt	5	0.0134*
Siteyr	6	<.0001*
Siteyr*Trt	30	0.3958
Coeff Var (C.V.)		33

*significant at P<0.05
[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment
[b]Means within columns followed by the same letter are not significantly different (*P*<0.05)

Generally, K fertilization is expected to have a larger effect on K concentration in the tissue than on early season dry matter yield (Clover and Mallarino 2013). Furthermore, the effect of K fertilization on K concentration is expected to be greater in UMT leaves than in the WP (Clover and Mallarino 2013; Stammer and Mallarino 2018). The effect of K fertilizer treatment on K concentration of the UMT leaves at R2 varied with site-year (Table 2.11). As with WP K concentration, fertilizer treatment led to significant increases in UMT K concentrations at Portage la Prairie 2017 and Bagot 2018. The other five site-years did not have significant differences in UMT K concentration between treatments. At Portage la Prairie 2017, the high rate of K sidebanded, low and high rate of K broadcast and incorporated treatments, all had significantly greater UMT K concentrations than in the control. However, the low rate of K sidebanded and mid-rate of K broadcast and incorporated treatments did not have significantly higher K concentrations compared to the control. At Bagot 2018, the trend was similar to Portage la Prairie 2017 for the mid and high rates of K; however, the K concentrations in the UMT for the low rate of K broadcast and incorporated treatment was not significantly greater than the control. Similar to the observations for WP K concentrations, UMT measurements indicate that rate of K fertilizer application appeared to have more effect on K concentration than placement at these site-years.

A study in Arkansas found soybean trifoliate tissue between the R1 and R2 growth stages with less than 15 g K kg^{-1} generally indicated there would be a yield response to K fertilization (Slaton et al. 2010). An Ontario study found the critical concentration of soybean trifoliate leaves to be much higher, 24.3 g K kg^{-1} (Yin and Vyn 2004). However, that study evaluated K concentration at R1 and was conducted at only three locations with a total of 9 site-years. More recently, Stammer and Mallarino (2018) assessed soybean yield response to K fertilization across 52 site-years to establish a critical concentration range for soybean leaf tissue. With linear-plateau and quadratic-plateau models (R^2 values of 0.51) they determined that the critical range was 15.6 to 19.9 g K kg^{-1} for UMT leaves at R2-3. Using this critical concentration range, which was established with sampling methodology that was similar to our study, the only site-year where every treatment was above the critical range was Long Plain 2018. At this site-year, even the control with no added K had a UMT K concentration of 21.5 g K kg^{-1}. Conversely, at Portage la Prairie 2017, the only treatment that raised the UMT K concentration above the critical range was 132 kg K_2O ha^{-1} broadcast and incorporated. At Bagot 2018, the K concentration of the control was in the critical range, but every K fertilization treatment regardless of rate and placement resulted in an increase in K concentration above the critical range. Therefore, there was no consistent pattern across site-years for the UMT tissue K concentration to be less than the critical level in the unfertilized treatment and above the critical level in fertilized treatments.

Table 2.11 Effect of K fertilization on uppermost mature trifoliate leaf K concentration for each site-year

Treatment[a]	Site-Year[b]						
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot
	2017	2017	2017	2017	2018	2018	2018
				g kg^{-1}			
0 kg K_2O ha^{-1}	20.8*a*	15.3*a*	20.3*a*	14.8*b*	18.8*a*	21.5*a*	17.0*b*
33 kg K_2O ha^{-1} SB	19.5*a*	16.0*a*	18.8*a*	18.0*ba*	19.3*a*	21.5*a*	20.3*ba*
66 kg K_2O ha^{-1} SB	19.8*a*	16.3*a*	20.3*a*	19.5*a*	19.8*a*	22.8*a*	24.3*a*
33 kg K_2O ha^{-1} BI	21.0*a*	15.8*a*	19.8*a*	19.3*a*	20.3*a*	20.5*a*	20.5*ba*
66 kg K_2O ha^{-1} BI	21.3*a*	16.8*a*	19.8*a*	19.8*ba*	19.3*a*	20.8*a*	23.0*a*
132 kg K_2O ha^{-1} BI	20.5*a*	17.8*a*	19.8*a*	21.8*a*	18.8*a*	23.8*a*	23.0*a*

ANOVA	df	*Pr>F*
Trt	5	0.0002*
Siteyr	6	0.0002*
Siteyr*Trt	30	0.0283*
Coeff Var (C.V.)		15

*significant at $P<0.05$

[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment

[b]Means within columns followed by the same letter are not significantly different ($P<0.05$)

Stem K concentration followed a similar trend as UMT K, with significant differences between treatments at Portage la Prairie 2017 and Bagot 2018 (Table 2.12). The treatments that had greater stem K concentrations compared to the control were the same as those resulting in greater UMT K concentration for each site-year. Although the numerical values of stem K concentration are greater than UMT K, the magnitude of difference between the control and treatments are generally similar for the two plant tissues. Use of stem K concentration as a diagnostic tissue test for soybean K nutrition status has not been very well documented in the literature. Fernández et al. (2009) found stem K concentration of soybean to be most similar to petiole K concentration and that the sum of petiole and stem K was generally greater than the K concentration of trifoliate leaves at the R2-3 growth stages. However, this research did not establish a critical concentration range for stem K. Despite its current lack of use as a diagnostic tool, the similarity in trends with K concentration for different K fertilization treatments between UMTs and stem samples suggest it could be a viable tissue sampling method if reliable critical concentration ranges were developed. However, stem sampling is more destructive than UMT leaf sampling.

Table 2.12 Effect of K fertilization on stem K concentration for each site-year

Treatment[a]	Site-Year[b]						
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot
	2017	2017	2017	2017	2018	2018	2018
				g kg^{-1}			
0 kg K_2O ha^{-1}	52.0*a*	40.3*a*	52.3*a*	36.0*c*	36.3*a*	33.0*a*	37.3*b*
33 kg K_2O ha^{-1} SB	50.8*a*	39.0*a*	50.5*a*	41.0*b*	37.5*a*	38.0*a*	44.0*ba*
66 kg K_2O ha^{-1} SB	50.5*a*	36.8*a*	55.0*a*	48.3*bc*	40.5*a*	35.8*a*	48.5*a*
33 kg K_2O ha^{-1} BI	54.3*a*	43.5*a*	51.3*a*	48.3*ba*	40.0*a*	33.0*a*	44.3*ba*
66 kg K_2O ha^{-1} BI	52.3*a*	41.3*a*	54.3*a*	47.0*ba*	40.0*a*	36.8*a*	46.3*a*
132 kg K_2O ha^{-1} BI	56.0*a*	43.5*a*	49.3*a*	54.8*a*	40.5*a*	39.3*a*	47.0*a*

ANOVA	df	*Pr>F*
Trt	5	<.0001*
Siteyr	6	<.0001*
Siteyr*Trt	30	0.0094*
Coeff Var (C.V.)		18.3

*significant at P<0.05
[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment
[b]Means within columns followed by the same letter are not significantly different (*P*<0.05)

2.4.4 Seed Yield at Maturity

There was no significant effect of K fertilization on soybean seed yield for any site-year (Table 2.13). This was not anticipated given that sites were selected where STK was low, soybean has a high demand for K and visual symptoms of K deficiency were observed at multiple site-years (Figure 2.4). Spring background STK concentrations were relied on to select sites likely to respond to K, based on the current 100 mg kg^{-1} threshold for recommendation of K fertilization in MB. However, the relationships between STK and relative seed yield for the control vs. K fertilized treatments in our study indicated no statistically significant or agronomically meaningful relationship between these two parameters for sites with less than 100 mg kg^{-1} STK (Fig 2.5). The yield response data were anticipated to follow a linear-plateau trend, with an inflection point of approximately 100 mg kg^{-1} STK. The lack of a relationship between relative seed yield and STK is evident for both broadcast and incorporated treatments, as well as sidebanded treatments, and the relationship did not improve when NH_4OAc K was determined on moist soil (Fig 2.6).

Table 2.13 Effect of K fertilization on seed yield at maturity for each site-year

Treatment[a]	Site-Year[b]							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot	All Sites
	2017	2017	2017	2017	2018	2018	2018	2017-2018
				kg ha^{-1}				
0 kg K_2O ha^{-1}	3501	2597	2325	2331	959	1288	2398	2200
33 kg K_2O ha^{-1} SB	3427	2566	2143	2306	1070	1284	2200	2142
66 kg K_2O ha^{-1} SB	3242	2968	2191	2562	923	1399	2258	2220
33 kg K_2O ha^{-1} BI	3583	2818	2197	2518	863	1556	2428	2281
66 kg K_2O ha^{-1} BI	3558	3009	2125	2344	876	1434	2278	2232
132 kg K_2O ha^{-1} BI	3217	2664	2262	2389	922	1527	2202	2169
Site-Year	3422*a*	2769*ba*	2210*b*	2412*b*	936*c*	1415*c*	2297*b*	

ANOVA	df	*Pr>F*
Trt	5	0.4542
Siteyr	6	<.0001*
Siteyr*Trt	30	0.6861
Coeff Var (C.V.)		39

*significant at P<0.05
[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment
[b]Means within rows followed by the same letter are not significantly different (*P*<0.05)

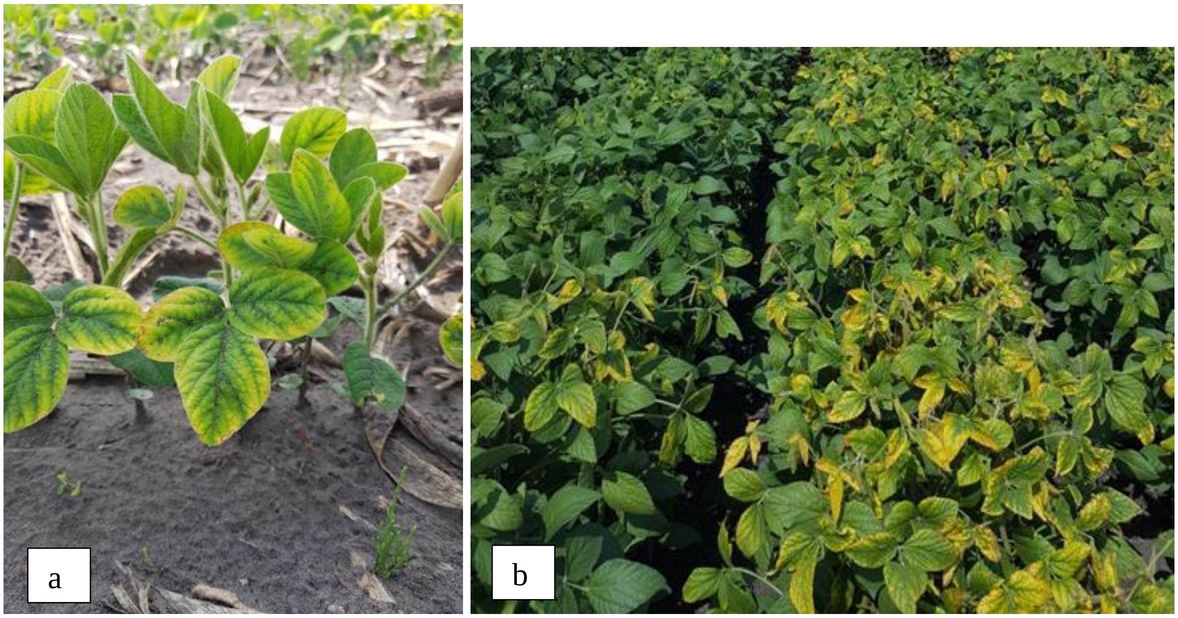

Figure 2.4 a) K deficiency symptoms at V2 growth stage at Bagot 2018, b) K deficiency symptoms at R5 growth stage at Haywood 2017

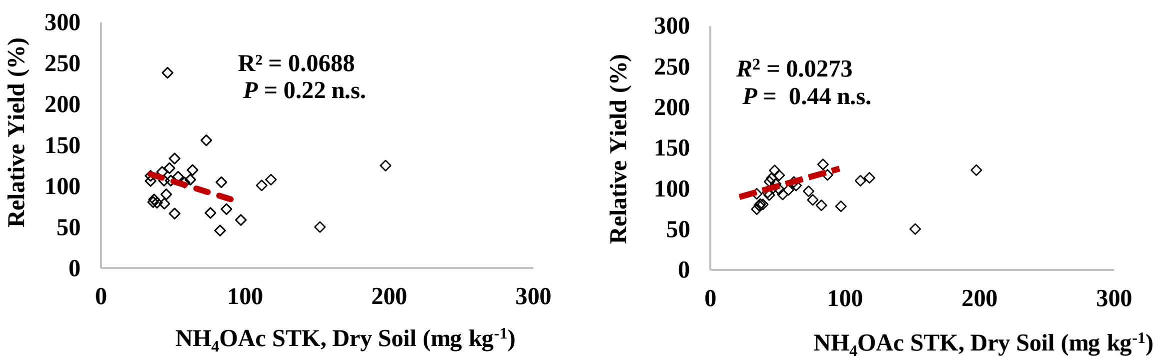

Figure 2.5 Relationship between concentration of NH_4OAc soil test K (STK) from 0-15 cm soil depth, determined on a dry soil sample, and relative yield of the control as a percent of yield for 66 kg K_2O ha^{-1} broadcast and incorporated (left), and 66 kg K_2O ha^{-1} sidebanded (right), with *P*-values and R^2 values for the data points less than or equal to 100 mg kg^{-1} STK

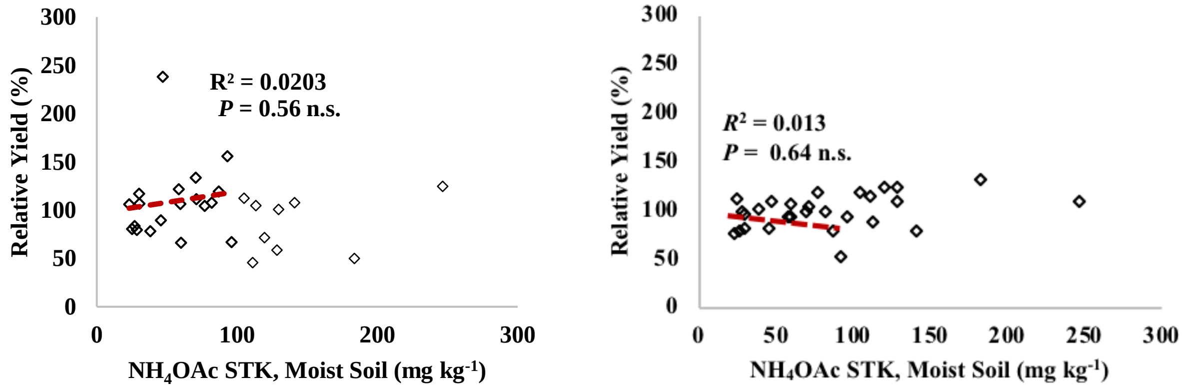

Figure 2.6 Relationship between concentration of NH_4OAc soil test K (STK) from 0-15 cm soil depth, determined on a moist soil, and relative yield of control as a percent of yield for 66 kg K_2O ha^{-1} broadcast and incorporated (left), and 66 kg K_2O ha^{-1} sidebanded (right), with *P*-values and R^2 values for the data points less than or equal to 100 mg kg^{-1} STK

Although there was a statistically significant difference between the quantity of STK determined on a moist versus a dry soil sample, the main basis for exploring the alternative methodology was to investigate whether it was more strongly related to yield response than the standard practice of dry soil K extraction. The lack of relationship between STK determined on a moist soil and relative yield indicates that there is little or no benefit for changing to this more complex and involved methodology. However, the standard practice dry K extraction was not related with relative yield either, and traditional NH_4OAc extraction from a spring soil test failed to predict where yield response would occur. Lack of evidence for any such relationship in this data set suggests the NH_4OAc test for exchangeable K was not a reliable indicator of soybean K responsiveness for these site-years and/or the NH_4OAc STK threshold of 100 mg kg^{-1} is too high for soybean in MB. These problems with the relationship between NH_4OAc STK and response to K fertilizer are similar to the findings of Breker et al. (2019) in North Dakota, who did not find a significant relationship between relative yield of corn and NH_4OAc STK determined on a dry soil basis in the first year of their study. As a result, they investigated other methodologies including resin K and tetraphenyl boron K, which quantify some portion of nonexchangeable K in addition to the solution and exchangeable pools. However, they did not find these alternate soil test methods improved prediction of corn yield response.

The inability of the NH_4OAc test to be a reliable predictor of soybean yield response to fertilizer K could have been related to sub-optimal environmental conditions and spatial variability within sites. The lack of sufficient growing season moisture in both the 2017 and 2018 growing seasons was certainly a yield-limiting factor, especially on these coarse-textured soils, and was probably the factor most limiting to yield, suppressing the capacity of soybean to respond to K fertilization. With adequate precipitation to achieve maximum yields, the soybeans would have demanded more K and K fertilization might have increased yield. The increase in tissue K concentration for some site-years, discussed in section 2.4.3, indicates that some added fertilizer K was taken up by the soybeans. If prevailing environmental conditions had supported increased yield potential, increasing the demand for K, this increase in tissue K concentration could have been a precursor to yield response. Additionally, large variability in STK values within site-years, compounded by stress due to lack of moisture, could have masked yield responses that may have been observed if background K concentrations and moisture supplies across plots had been more consistent.

Therefore, with more growing season rainfall and yield potential, and more uniform site-year STK concentrations, the NH_4OAc test may have been a more reliable indicator of K response. However, there could also be a discrepancy between NH_4OAc exchangeable K measured with a static lab extraction and actual bioavailable K accessible to a growing crop over the course of a season due to the release of nonexchangeable soil K. Several studies have documented the contribution of nonexchangeable K to crop K nutrition (Havlin and Westfall

1985; McLean and Watson 1985; Brar et al. 2016). The challenge is to quantify the contribution of the nonexchangeable K pool for the duration of a growing season. The lack of improvement in K fertilizer yield response prediction when soil test methodologies that quantify some portion of nonexchangeable K in addition to available K, such as resin and sodium tetraphenylboron extractions, in Breker et al. (2019), demonstrates the challenge of finding efficacious and practical laboratory procedures to improve quantification of bioavailable K for a growing season.

Additionally, plant genetics plays a role in the efficiency of soybean K uptake and use (Rengel and Damon 2008). Therefore, K response in our study may have been greater if a more responsive soybean variety had been planted.

2.4.5 Seed Potassium Concentration and Quality

Potassium treatments had a similar effect on seed K concentration across all site-years, with no significant site-year x treatment interaction indicated in the ANOVA (Table 2.14). The highest rate of K fertilization at each placement, 66 kg ha^{-1} sidebanded and 132 kg ha^{-1} broadcast and incorporated, produced significantly higher seed K concentration than the control. All other treatments resulted in seed K concentrations that were similar to each other and the control. As with the midseason tissue concentrations, this suggests K fertilizer rate had a greater contribution to seed K concentration than placement at the study site-years. The magnitude of difference in seed K concentration between the control and fertilized treatments was smaller than the difference in tissue K concentration. This is similar to other studies, where researchers observed greater effects of K fertilization on tissue K concentrations compared to seed K concentrations (Fernández et al. 2009).

Table 2.14 Effect of K fertilization on seed K concentration for each site-year

Treatment[a]	Site-year[b]							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot	All sites
	2017	2017	2017	2017	2018	2018	2018	2017-2018
			g kg^{-1}					
0 kg K_2O ha^{-1}	16.3	15.5	19.3	16.8	18.0	16.8	16.3	17.0*b*
33 kg K_2O ha^{-1} SB	16.8	17.5	19.8	16.8	18.8	17.0	16.8	17.6*ba*
66 kg K_2O ha^{-1} SB	17.5	17.8	19.5	19.3	19.5	17.8	16.3	18.2*a*
33 kg K_2O ha^{-1} BI	16.3	17.3	19.5	16.3	18.5	16.3	16.0	17.1*b*
66 kg K_2O ha^{-1} BI	17.3	16.5	19.8	18.5	18.8	18.0	17.3	18.0*a*
132 kg K_2O ha^{-1} BI	17.3	18.8	19.5	17.0	19.5	17.5	17.3	18.1*a*

ANOVA	Df	*Pr>F*
Trt	5	<.0001*
Siteyr	6	0.0006*
Siteyr*Trt	30	0.2813
Coeff Var (C.V.)		9

*significant at P<0.05

[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment

[b]Means within columns followed by the same letter are not significantly different (P<0.05)

Parvej et al. (2016b) suggested seed K concentration could be used as a post-season diagnostic tool for K deficiency and suggested a critical seed K concentration range of 14.6 -16.2 g kg^{-1} based on 24 Canadian site-years. Using this range, only the control of Haywood 2017 was below the upper limit. This suggests that at all other site-years, soil K supply, without the addition of K fertilizer, was sufficient to exceed the critical seed K concentration threshold. This indication of adequate K nutrition for the majority of treatments, including the controls, at each site-year contrasts with the threat of deficiency that was apparently present at most site-years according to midseason UMT K concentrations. Given the small amount of growing season precipitation, the effect of the drought-like conditions would have been exacerbated as the growing season progressed and soil moisture supplies were depleted. As a result, yield potential likely declined, decreasing the demand for K and diminishing the benefit of K fertilization by the end of the growing season. Differences in K concentration persisted only in the treatments that had the highest rate of K fertilizer for both placements. This, coupled with the lack of yield response, suggest only subtle differences in K nutrition with K fertilization for these site-years in the prevailing moisture-limited growing conditions. Under better growing conditions, the differences detected midseason may have been magnified and persistent through the duration of the growing season.

Potassium fertilization did not affect seed oil or protein content (Table 2.15, 2.16). The lack of response in oil and protein content from K fertilization was not surprising, as the literature suggests K effects on oil and protein are inconsistent (Haq and Mallarino 2005; Krueger et al. 2013) and that the environment may have a larger role than K fertilizer for influencing seed quality parameters (Miranda et al. 2014).

Table 2.15 Effect of K fertilization on seed protein content

Treatment[a]	Protein (%)[b]	
0 kg K_2O ha^{-1}	33.3	
33 kg K_2O ha^{-1} SB	33.1	
66 kg K_2O ha^{-1} SB	33.3	
33 kg K_2O ha^{-1} BI	33.3	
66 kg K_2O ha^{-1} BI	33.2	
132 kg K_2O ha^{-1} BI	33.1	
Site-year		
Elm Creek 2017	33.8*a*	
Haywood 2017	34.3*a*	
St. Claude 2017	28.9*b*	
Portage la Prairie 2017	34.1*a*	
Haywood 2018	33.7*a*	
Long Plain 2018	34.6*a*	
Bagot 2018	33.8*a*	
ANOVA	df	*Pr>F*
Treatment	5	0.7189
Site-year	6	<0.0001*
Site-year*Treatment	30	0.7014
Coeff Var (C.V.)		6

*significant at P<0.05

[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment

[b]Means within columns followed by the same letter are not significantly different (*P*<0.05)

Table 2.16 Effect of K fertilization on seed oil content

Treatment[a]	Oil (%)[b]	
0 kg K_2O ha^{-1}	18.2	
33 kg K_2O ha^{-1} SB	18.4	
66 kg K_2O ha^{-1} SB	18.3	
33 kg K_2O ha^{-1} BI	18.2	
66 kg K_2O ha^{-1} BI	18.3	
132 kg K_2O ha^{-1} BI	18.4	
Site-year		
Elm Creek 2017	17.2*b*	
Haywood 2017	17.4*b*	
St. Claude 2017	19.5*a*	
Portage la Prairie 2017	17.4*b*	
Haywood 2018	18.9*a*	
Long Plain 2018	19.2*a*	
Bagot 2018	18.5*ab*	
ANOVA	df	*Pr>F*
Treatment	5	0.4226
Site-year	3	<0.0001*
Site-year*Treatment	30	0.1177
Coeff Var (C.V.)		6

*significant at P<0.05
[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment
[b]Means within columns followed by the same letter are not significantly different (*P*<0.05)

2.4.6 Overall Discussion

Due to the lack of seed yield response for any site-year, the ideal rate and placement combination for K fertilization of soybean in Manitoba could not be determined. Although there were no significant differences in seed yield between control and K fertilized plots, the effect of K fertilization on midseason K uptake, tissue concentrations, and seed K concentration at harvest indicate subtle differences in the efficacy of K fertilizer rate and placement for improving soybean K nutrition. The K uptake data suggest sidebanded placement may improve K nutrition over broadcast and incorporated placement; however, this increase in K uptake did not result in soybean biomass yield differences at the R2 growth stage. Additionally, the WP, UMT and stem

K concentration data suggest the alternate, that K fertilizer rate had a greater effect than placement on soybean K nutrition. Generally, for the two responsive site-years, the higher rates at both placements resulted in significant increases in tissue K concentration compared to the control, but the sidebanded and broadcast placements were not statistically different from one another. Similarly, only the highest rate of K fertilization at both placements led to significantly greater seed K concentration than the control, but the seed K concentrations for the highest rate of each placement were not significantly different from one another. Therefore, both the midseason tissue K and seed K concentrations suggest K fertilizer rate had a greater effect on soybean K nutrition than placement. Since the diffusive ability of K in the soil is greater in soil with lower K buffering capacity (Bell et al. 2009) and soils with a lower K buffering capacity have lower cation exchange capacity (CEC), the lack of significant effect of placement on K nutrition could have resulted from the coarse textured soils at these site-years. Coarse textured soils in MB generally have lower CECs; however, soil CEC was not measured in this experiment.

Comparing UMT K concentrations to established critical ranges also indicates the importance of K fertilizer rate for midseason soybean K nutrition. Except at Long Plain 2018, where every treatment and the control UMT K concentration were above the critical range, the threat of K deficiency at midseason was present at all other site-years. However, by the end of the season, the midseason differences between treatments had diminished and the effect of K fertilization was more subtle. Even though the highest K fertilizer rate for both placements led to significant increases in seed K concentration, all seed K concentrations for each site-year, except the control at Haywood 2017, were above the established critical range for post-season diagnosis of K deficiency. The diminishing effect of K fertilization on K nutrition indicators, and the lack of effect on seed yield, are likely explained at least in part by the combination of sub-optimal environmental conditions and variability within sites. Inadequate growing season precipitation resulted in a decline of yield potential as the season progressed. A lower yield potential requires less K to meet the needs of smaller plants; as yield potential declined between growth stage R2 when midseason samples were collected and the end of the growing season, K nutritional status of the soybean plants generally shifted from a risk of K deficiency to sufficiency. The differences in midseason tissue K concentration present at Portage la Prairie 2017 and Bagot 2018, and the overall effect of K fertilization on seed K concentration, suggest there might have been an opportunity for K fertilization to increase soybean K nutrition and seed yield. Under better growing conditions where moisture is not limiting, the midseason benefits of K fertilization on tissue K concentration might be realized in increased seed yield. However, the probability of moisture conditions being less than optimum for soybean production in Manitoba is high and the modest yield potential of these small plot trials may be typical for this area. Average seed yields for all treatments and site-years were 2703 kg ha^{-1} in 2017 and 1549 kg ha^{-1} in 2018, not hugely different from Manitoba's average soybean yield of 2370 kg ha^{-1} for 2015-2019 (Statistics Canada 2020). Therefore, soybean crops in Manitoba may not require as much K as those that are grown where late season moisture supplies and seed yield potential are greater.

In addition to environmental considerations affecting the contribution of K fertilization to seed yield, variability in STK concentration and the lack of an effective soil test methodology to predict yield response to K fertilization for soybean are in question. In order to determine the ideal rate and placement of K fertilizer for soybean production, responsive soils are required. Our study demonstrates the challenge of characterizing potential responsiveness of site-years for soybean using the traditional STK methods commercially available to growers in MB. The site-years where this study was conducted were classified as low in STK, yet there was no yield response to K fertilization. The absence of a statistically significant or agronomically meaningful relationship between STK, determined from a moist soil sample or a dry soil sample, and relative yield calls into question the validity of this test as an indicator of soybean K response and/or the 100 mg kg^{-1} threshold at which K fertilization is recommended. However, these soil testing challenges might be specific to soybean, since traditional STK reliably predicted yield response to K fertilization in barley at our sites in 2018 (Appendix IV). In 2018 only, a K responsiveness study comparing the K response of barley and soybean was conducted at each of the soybean small plot site locations. Barley seed yield significantly increased with K fertilization, but soybean seed yield did not. The significant barley seed yield increase was anticipated based on the low STK concentrations at each location. Therefore, STK can reliably predict K response in other crops, such as barley, but may not be suited to predicting soybean seed yield response to K in coarse textured soils of MB.

In addition to the traditional soil test K methods commercially available to growers, soil K supply rates were characterized for each site-year using PRS® probes available through Western Ag Innovations. Assessing the PRS® K supply rates at the two site-years where K fertilization increased tissue K concentration and K uptake, the results were surprising. Bagot 2018 had PRS® K supply rates an order of magnitude smaller than those measured at Portage la Prairie 2017, despite similar spring ammonium acetate exchangeable K concentrations at these two sites. Given its much smaller K supply rate, Bagot 2018 would have been expected to have lower K uptake and tissue concentrations than Portage la Prairie 2017. However, this is not what occurred; Bagot 2018 had more K uptake than Portage la Prairie 2017 in each K fertilization treatment as well as the control. Additionally, K fertilization treatments were more effective at increasing UMT K concentration above the critical range at Bagot 2018 compared with Portage la Prairie 2017.

2.5 Conclusions

The K fertilizer rate and placement combination best suited to increasing soybean seed yield could not be determined due to lack of yield response to K fertilization. Therefore, we were not able to conclusively prove or disprove our hypotheses that higher rates of K fertilizer would increase soybean K response and banded placement would be more effective at increasing soybean K uptake and seed yield than broadcast placement. Given the low STK concentration for each site-year and the increase in PRS® K supply rate with K fertilization at most site-years, a greater number of site-years were expected to have tissue K concentration and seed yield responses to K fertilization. However, the significant K concentration increases for WP, UMT and stem tissue at two of the site-years suggest K fertilizer rate appeared to have a greater effect on K nutrition of soybean than placement.

Overall, soil related measurements indicate that the relationships between various types of measurements for STK varied with site-year. The differences in relationships between MK and DK at different depths, the burial period x site-year and treatment x site-year interaction for PRS® K supply rates indicate substantial site-to-site variability in K behaviour.

Although K fertilization did not increase seed yield at any of our site-years, midseason measurements indicated the potential opportunity for K fertilization to improve soybean K nutrition and seed yield under better late-season growing conditions. However, predicting where that yield response would occur based on STK concentration and parameters influencing K supply rate are yet to be confidently determined. Further research is required to determine what soil test method and threshold best predicts soybean yield response to K fertilization.

Additionally, investigation into the mechanisms of soil K supply over the growing season and the relationship between STK and bioavailable K would be valuable for developing K fertilization strategies for soybean. Once soybean K response can be more reliably predicted, investigation into the K fertilizer rate and placement combination best suited to increasing seed yield on coarse textured soils of MB should be readdressed.

2.6 References

Barbagelata, P.A., and Mallarino, A.P. 2012. Field correlation of potassium soil test methods based on dried and field-moist soil samples for corn and soybean. Soil Sci. Soc. Am. J. **77**: 318–327.

Bell, M.J., Moody, P.W., Harch, G.R., Compton, B., and Want, P.S. 2009. Fate of potassium fertilisers applied to clay soils under rainfed grain cropping in south-east Queensland, Australia. Aust. J. Soil Res. **47**: 60–73.

Borges, R., and Mallarino, A.P. 2003. Broadcast and deep-band placement of phosphorus and potassium for soybean managed with ridge tillage. Soil Sci. Soc. Am. J. **67**: 1920–1927.

Brar, B.S., Romana, P.S., and Saini, S.P. 2016. Long-term chemical fertilization impacts on kinetics of K release, wheat yield, and K uptake in a typic ustrochrept soil of Punjab, India. J. Crop Improv. **30**: 47–64.

Breker, J.S. 2017. Recalibration of soil potassium test for corn in North Dakota. M.Sc. thesis, North Dakota State University, Fargo, ND. 170 pp.

Breker, J.S., DeSutter, T., Rakkar, M.K., Chatterjee, A., Sharma, L., and Franzen, D.W. 2019. Potassium requirements for corn in North Dakota: Influence of clay mineralogy. Soil Sci. Soc. Am. J. **83**: 429–436.

Clover, M.W., and Mallarino, A.P. 2013. Corn and soybean tissue potassium content responses to potassium fertilization and relationships with grain yield. Soil Sci. Soc. Am. J. **77**: 630–642.

Farmaha, B.S., and Nafziger, E.D. 2012. Soybean seed composition, aboveground growth, and nutrient accumulation with phosphorus and potassium fertilization in no-till and strip-till. Agron. J. **104**: 1006–1015.

Fernández, F.G., Brouder, S.M., Volenec, J.J., Beyrouty, C.A., and Hoyum, R. 2009. Root and shoot growth, seed composition, and yield components of no-till rainfed soybean under variable potassium. Plant Soil **322**: 125–138.

Gaspar, A.P., Laboski, C.A.M., Naeve, S.L., and Conley, S.P. 2017. Phosphorus and potassium uptake, partitioning, and removal across a wide range of soybean seed yield levels. Crop Sci. **57**: 2193–2204.

Haq, M.U., and Mallarino, A.P. 2005. Response of soybean grain oil and protein concentrations to foliar and soil fertilization. Agron. J. **97**: 910–918.

Havlin, J.L., and Westfall, D.G. 1985. Potassium release kinetics and plant response in calcareous soils. Soil Sci. Soc. Am. J. **49**: 366–370.

Kaiser, D. 2017. Low commodity prices and fertilizer management – where do we go from here? [Online] Available: https://mawrc.org/wp-content/uploads/2017/02/0.2-Kaiser-Fertilizer Recommendations-Update.pdf [10 June 2020].

Krueger, K., Susana Goggi, A., Mallarino, A.P., and Mullen, R.E. 2013. Phosphorus and potassium fertilization effects on soybean seed quality and composition. Crop Sci. **53**: 602–610.

Licht, M.A., Wright, D., and Lenssen, A.W. 2013. Soybean Response to Drought. [Online] Available: https://lib.dr.iastate.edu/extension_ag_pubs/190 [29 June 2020].

Manitoba Agriculture. 2007. Manitoba Soil Fertility Guide. [Online] Available: https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/pubs/soil_fertility_guide.pdf [24 Jan. 2019].

Manitoba Agriculture. 2019. Yield Manitoba. [Online] Available: https://www.masc.mb.ca/masc.nsf/ym_2019_full_issue.pdf [10 June 2020].

Manitoba Pulse and Soybean Growers (MPSG). 2018. Water limitations in pulse and soybean crops. [Online] Available: https://www.manitobapulse.ca/2018/06/water-limitations-in-pulse-and-soybean-crops/ [6 Aug. 2019].

McLean, E.O., and Watson, M.E. 1985. Soil measurements of plant-available potassium. *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI.

Miranda, D.H., Carvalho, M.L.M. de, Zambiazzi, E.V., Soares, I.O., Bruzi, A.T., Rezende, P.M. de, and Zuffo, A.M. 2014. Potassium fertilization and physiological soybean seed quality. Agric. Sci. **5**: 984–991.

Murage, P.M. 1984. Potassium as a limiting nutrient for maximum production of wheat in Manitoba. M.Sc. thesis, University of Manitoba, Winnipeg, MB. 164 pp.

Nkebiwe, P.M., Weinmann, M., Bar-Tal, A., and Müller, T. 2016. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. F. Crop. Res. **196**: 389–401.

Parvej, M.R., Slaton, N.A., Purcell, L.C., and Roberts, T.L. 2015. Potassium fertility effects yield components and seed potassium concentration of determinate and indeterminate soybean. Agron. J. **107**: 943–950.

Parvej, M.R., Slaton, N.A., Purcell, L.C., and Roberts, T.L. 2016a. Soybean yield components and seed potassium concentration responses among nodes to potassium fertility. Agron. J. **108**: 854–863.

Parvej, M.R., Slaton, N.A., Fryer, M.S., Roberts, T.L. and Purcell, L.C. 2016b. Postseason Diagnosis of potassium deficiency in soybean using seed potassium concentration. Soil Sci. Soc. Am. J. **80**: 1231-1243.

Pratt, P.F. 1965. Potassium. Pages 1022–1030 *in* Methods of Soil Analysis. Amer. Soc. Agron., Madison, WI.

Qian, P., and Schoenau, J.J. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. Can. J. Soil Sci. **82**: 9–21.

Rakkar, M.K., Franzen, D., and Chatterjee, A. 2016. Is air-drying of soil samples an appropriate step in determining plant available potassium for corn? J. Plant Nutr. **39**: 1979–1988.

Rengel, Z. and Damon, P.M. 2008. Crops and genotypes differ in efficiency of potassium uptake and use. J. Physiol. Plant. **133**: 624-636.

SAS Institute. 2018. The SAS system for Windows. Release 9.4. SAS Inst., Cary, NC.

Slaton, N.A., Golden, B.R., DeLong, R.E., and Mozaffari, M. 2010. Correlation and calibration of soil potassium availability with soybean yield and trifoliolate potassium. Soil Sci. Soc. Am. J. **74**: 1642–1651.

Stammer, A.J., and Mallarino, A.P. 2018. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean. Soil Sci. Soc. Am. J. **82**: 260–270.

Statistics Canada 2018. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. [Online] Available: http://www5.statcan.gc.ca/cansim/a47 [12 Jan 2018].

Statistics Canada 2020. Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units. [Online] Available: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210035901 [26 June 2020].

Usherwood, N.R. 1985. The role of potassium in crop quality. Pages 489–513 *in* Munson, R.D., ed. Potassium in Agriculture. ASA-CSSA-SSSA, Madison, WI.

Yin, X., and Vyn, T.J. 2002. Soybean responses to potassium placement and tillage alternatives following no-till. Agron. J. **94**: 1367–1374.

Yin, X., and Vyn, T.J. 2004. Critical leaf potassium concentrations for yield and seed quality of conservation-till soybean. Soil Sci. Soc. Am. J. **68**: 1626–1634.

3. FREQUENCY OF SOYBEAN YIELD RESPONSE TO POTASSIUM FERTILITY AND FERTILIZER IN MANITOBA: ON-FARM TRIALS

3.1 Abstract

Until 2017, only two site-years of data had been generated in Manitoba (MB) to assess soybean [*Glycine max* (L.) Merr] seed yield response to potassium (K) fertilization. To determine plant tissue and seed yield response to added K and investigate the background ammonium acetate soil test K (STK) concentrations where yield response occurs, on-farm trials were established in conjunction with the Manitoba Pulse and Soybean Growers (MPSG) through the On-Farm Network (OFN). Over the 2017 and 2018 field seasons, data were collected from a total of 20 site-years with a range in background STK from 52 - 451 mg kg^{-1}. Sites were replicated field-scale strip trials, with a control (no K fertilizer) and one treatment of either 66 kg K_2O ha^{-1} banded away from the seed or 132 kg K_2O ha^{-1} broadcast and incorporated. Strip yield data were collected by MPSG in cooperation with producers to characterize soybean yield response to K fertilization at a field scale. Three site-years had significant yield response to K fertilization with one site-year responding negatively and two responding positively. Site background STK was not a reliable predictor of yield response, and there was no agronomically meaningful relationship between STK and relative yield. Paired midseason soil and plant tissue samples, seed yield and K concentration at maturity, were taken from microplots within each site-year to investigate K responsiveness at a more detailed scale within each field-scale strip trial. Midseason samples indicated that K fertilization significantly increased microplot tissue K concentration at three site-years. Significant seed yield increases occurred in microplots at two site-years, both of which did not have significant midseason tissue K concentration differences between treated and untreated microplots. Application of K fertilizer increased seed K

concentration in microplots at two site-years, including one site-year where K fertilization increased microplot seed yield. A third site-year had a significant decline in microplots' seed K concentration with K fertilization and this was also a site-year where K fertilization increased microplot seed yield.

3.2 Introduction

As soybean production has expanded in Manitoba (MB), particularly into coarse textured areas of the province where the soil may be inherently low in K, there has been an increase in the incidence of soybean K deficiency symptoms. Given the lack of comprehensive historical K fertility research for soybean in MB, likely a result of the previously small production area of soybean in the province, there are very few data on characterization of frequency of soybean yield response to K fertilization. Of particular interest is the relationship between background ammonium acetate soil test K (STK) concentration and yield response to K fertilization, to enable reliable prediction of soybean yield response to K fertilization based on STK concentration.

Current STK thresholds for recommending an application of K fertilizer on soybean in MB are lower than those recommended in neighbouring soybean producing regions. Manitoba's current STK threshold for recommending application of K fertilizer is 100 mg kg^{-1}; whereas Minnesota recommends K fertilization for soybean on any soil testing less than 200 mg kg^{-1} (Kaiser 2018), North Dakota for any soil less than 150 mg kg^{-1} (Franzen 2018) and Ontario for any soil less than 120 mg kg^{-1} [Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) 2017]. Additionally, the current 100 mg kg^{-1} threshold in MB, and the recommended K fertilizer rates, are the same for soybean as for other crops like spring wheat and canola which do not remove as much K per unit of grain produced as soybean. Investigation of the frequency of response across a range of STK concentrations is required to indicate if the 100 mg kg^{-1} threshold is appropriate for current soybean production in MB.

In this study, both on-farm replicated strip trials and microplots within strip trials were utilized to investigate the frequency of soybean yield response to K fertilization across a range of STK concentrations. Generally, on-farm trials are a cooperation between the organizing body, producers and their agronomists. Producers establish, maintain and apply treatments to the trial with their own equipment, as on-farm research aims to establish statistically valid conclusions about management practices, products or technologies for producers' specific operations. Despite the lack of consistency in equipment and crop management practices, replicated strip trials at a field-scale can be used to investigate cause and effect relationships in a statistically meaningful capacity for parameters across or within fields [Iowa Soybean Association (ISA) 2016]. On-farm field-scale research can be very complementary to small plot research; generally, field-scale trials test the treatments that show the most responsiveness at a small plot scale. Field-scale trials are best suited to testing just one or two treatments compared to a control. Despite the reduction in treatment number, maintaining proper scientific principles of trial design, such as randomization and replication, are integral to preserving the validity of obtained results (Bowman 1994) and their utility in making management decisions on the farm.

Field scale on-farm trials investigate a different perspective and offer a different scope of inference compared to small plot trials. Small plot research can efficiently and effectively compare a large number of treatments in a relatively small and uniform area. Generally, small plot trials aim to isolate the effect of the treatment of interest as much as possible, so selection of a uniform site with limited background variability is important. The small spatial scale of these studies is intended to allow uniform site conditions within each trial (Bowman 1994). Field-scale trials are conducted over a much larger area than small plot trials. This increase in scale is usually accompanied by an increase in background variability within the trial area. However, unlike small plot trials, where variability is reduced or avoided as much as possible, field-scale trials may accommodate field variability with much larger areas for sample collection. This facilitates investigating the behaviour of response to treatments at the scale a producer would apply them, with all the variability that accompanies the scale of that application. On-farm research allows producers to characterize response on their individual farms, under their growing conditions, soil types and management practices, which may differ from the conditions on a designated research farm or station (Bowman 1994). This individualized approach to research is particularly important for investigation of parameters with large amounts of spatial variability. This is one of the challenges with characterizing soil K fertility and crop response to K; K is spatially variable across a field. This spatial variability has been demonstrated in several studies (Franzen and Peck 1997; Cook and Bramley 2000; Sawchik and Mallarino 2007) and such variability is visually evident within MB fields (Appendix III).

Strip yield data can be used to characterize site-year responsiveness at a field scale and determine frequency of response across a range of background concentrations of STK. However, at this field scale, characterization of variability in STK and soybean responsiveness to K fertilization within the trial is usually overlooked. As a result of in-field STK variability, some areas within the trial strips may have yield increases with K fertilization while others may not. Detailed investigation of the responsiveness to K fertilizer and the relationship with STK at a smaller spatial scale is possible through the establishment of microplots within larger on-farm trials.

Microplot measurements within strip trials can also be used for detailed measurements of plant tissue K at various stages of plant growth. Although, from a producer's perspective, the most important quantification of the efficacy of a K fertilization practice is an increase in seed yield, midseason tissue K concentration and seed K concentration at harvest are useful tools to determine whether K fertilizer was needed and/or utilized by the plants. Soybean leaf K concentrations at R2-3 are more strongly related to yield response than whole plant (WP) samples taken at the V5-6 stage (Clover and Mallarino 2013; Stammer and Mallarino 2018). However, a response in tissue K concentration detected midseason is not always predictive of yield response to K fertilization. Clover and Mallarino (2013) found a yield increase with K fertilization only when a tissue K concentration increase at R2-3 was detected, but there was not a yield increase in every case where there was a tissue K increase. That is, an increase in tissue K did not always predict an increase in seed yield.

Similarly, differences in seed K concentration with K fertilization are more likely to be detected where seed yield response occurred (Parvej et al. 2016), but there can be an increase in seed K concentration from K fertilization without a concurrent seed yield increase. Parvej et al. (2016) determined a seed K sufficiency range for Canadian soybeans of 14.6 to 16.2 g kg^{-1}. Just as tissue K concentration midseason and, perhaps, the presence of visual K deficiency symptoms can be used to determine the adequacy of a K fertilizer program, this seed K concentration sufficiency range can be used as a diagnostic tool to retroactively assess plant K nutrition status.

As soybean production has expanded in MB, producers are growing soybeans on an increasing land base where K fertility management is a concern. Manitoba's current STK thresholds and K fertilization recommendations are lower than those of neighbouring soybean producing regions. Therefore, the main purpose of this study was to investigate the relationship between the background STK concentrations and the frequency and magnitude of soybean yield response to K fertilization at two different spatial scales: field-scale strip trials and microscale paired plots within those strip trials. We hypothesized that frequency and magnitude of response would be greatest for low STK site-years, especially for those site-years with STK concentrations less than 100 mg kg^{-1}. Strip yield data were used to assess soybean K responsiveness at a field scale and the relationship between relative yield and background K fertility. Paired microplots were used to investigate the relationship between STK and relative yield, and to investigate the effect of K fertilization on soybean tissue K concentration, seed K concentration and seed yield. Relationships between STK and soybean relative yield at these two spatial scales were used to determine the sufficiency of the current threshold of 100 mg kg^{-1} STK for recommending an application of K fertilizer.

3.3 Materials and Methods

3.3.1 Site Selection and Description

Sites were selected primarily on the basis of producer interest in the study and to include a wide range of background STK concentrations. Producer knowledge of field history and STK concentrations from previous soil tests were utilized for preliminary assessment of site suitability. Prior to the field-scale strip trials, a composite fall or spring soil sample from each potential site was sent to Agvise Laboratories (Northwood, ND) for complete soil fertility analysis. Exchangeable K concentration was determined on a dried and ground soil sample that was extracted with 1 M ammonium acetate (pH 7.0.) at a 1:10 soil to solution ratio and measured with a Perkin Elmer 5400 ICP-OES. Site uniformity was also considered; however, given the large area of these trials, uniformity was difficult to achieve. Surface drains and headlands were avoided.

Selected trial locations targeted a range in background STK concentrations, up to 150 mg kg^{-1}, but included several trials that had background K concentrations higher than this, up to 450 mg kg^{-1} (Table 3.1). Evaluating the frequency of K fertilization responses across this wide range of background STK values allowed evaluation of the current STK threshold of 100 mg kg^{-1} and could suggest a new threshold for recommending K fertilization, depending on the frequency and pattern of response across the various concentrations of STK.

Fifteen on-farm K fertilization trials were established in 2017: near Portage la Prairie, MB (49˚52’59”N, 98˚47’08”W), St. Claude, MB (49˚34’21”N, 98˚19’05”W), Elm Creek, MB (49˚37’55”N, 97˚59’19”W), Bagot, MB (49˚55’38”N, 98˚38’48”W), Long Plain, MB (49˚87’94”N, 98˚60’84”W), Balmoral, MB, (50˚16’27”N, 97˚17’34”W), Beausejour, MB (50˚03’54”N, 96˚18’35”W), Miami, MB (49˚26’49”N, 98˚14’43”W), Swan River, MB (52˚03’35”N, 101˚19’02”W), Melita, MB (49˚22’25”N, 100˚56’07”W), Dencross, MB (50˚23’21”N, 96˚22’16”W), Riding Mountain, MB (51˚03’19”N, 100˚15’24”W), Dauphin, MB (51˚16’34”N, 100˚11’53”W), and Pansy, MB (49˚16’12”N, 96˚41’07”W). Five sites were established in 2018: near Swan River, MB (52˚07’05”N, 101˚31’10”W), Steinbach, MB (49˚26’50”N, 96˚35’03’W), Stonewall, MB (50˚13’21”N, 97˚20’21”W), Haywood, MB (49˚41’00”N, 98˚12’17”W) and Long Plain, MB (49˚50’46”N, 98˚25’13”W). All site-years were established in commercial fields. Background STK concentrations are listed in Table 3.1.

Table 3.1 Background ammonium acetate exchangeable soil test K (STK) concentrations at on-farm trials in Manitoba in spring 2017 and 2018

Site-Year	STK
	mg kg^{-1}
Portage la Prairie 2017	78
St. Claude 2017	88
Elm Creek 2017	107
Bagot 2017	105
Balmoral 2017	235
Beausejour 2017	87
Miami 2017	131
Swan River 2017	52[a] (162.5)[b]
Melita 2017	155
Dencross 2017	183
Riding Mountain 2017	139
Dauphin 2017	105
Pansy 2017	114
Long Plain 2017	not available
MacGregor 2017	130
Swan River 2018	450
Steinbach 2018	115
Stonewall 2018	216
Haywood 2018	87
Long Plain 2018	76

[a]From a field composite soil sample taken in fall 2016
[b]Value in parentheses is the composite midseason soil test K concentration from untreated areas

3.3.2 Field-Scale Strip Trial Experimental Design and Treatments

To complement the small plot research discussed in Chapter 2, each of the on-farm trials utilized a control without added K compared to one of two types of K fertilization treatments: 66 kg K_2O ha^{-1} banded away from the seed or 132 kg K_2O ha^{-1} broadcast and incorporated. These treated and untreated strips were organized as a randomized complete block design in the field. In this manner, the focus was on the occurrence and magnitude of yield response to K fertilization relative to the background STK concentration, rather than a comparison of the effectiveness of K rate and application method, which was the main focus of the small plot research in Chapter 2. The on-farm trials were established by MPSG's OFN, in cooperation with interested growers. The fertilized treatment at each location was determined by the producer's normal practice, e.g., whether they were equipped to broadcast and incorporate or had the ability to band the K fertilizer. Type of banding varied among site-years, but all bands were placed away from the seed to eliminate fertilizer toxicity risk. Banding operations included sideband and midrow band. All of the K fertilizer treatments were in the form of potassium chloride (potash, KCl, 0-0-60). Strip width and length at each site-year varied with producer equipment and field size. Generally, strips were at least as wide as a combine pass and extended the entire length of the field, excluding the headlands. There were four to six replications at each site-year. All other fertility and crop management decisions were at the producer's discretion, and the trial was managed and maintained by the producer in the same manner as the rest of the field.

3.3.3 Weather Conditions

The majority of water and nutrient uptake for soybean in MB generally occurs between the R1 and R5 growth stages (MPSG 2018), which typically extends from early-July to late August. Soybeans require more than 400 mm of water to achieve maximum yield potential (MPSG 2018) and timely precipitation during the period of peak water and nutrient uptake is important for maintaining yield potential. Apart from Stonewall 2018 and Swan River 2018, all on-farm trial site-years had less than normal precipitation from May to August. Even in a year with normal growing season precipitation, MB's moisture supplies are only marginally sufficient (Table 3.2). Therefore, lower than normal growing season precipitation was probably a yield limiting factor at most site-years in the 2017 and 2018 growing seasons.

Table 3.2 Growing season precipitation and percent of normal for May to August[a]

Site-Year[b]	May	June	July	August	Percent of Normal
	mm				
Elm Creek 2017	28	71	24	14	47%
Portage la Prairie 2017	27	70	30	9	47%
St. Claude 2017	29	66	27	24	50%
Bagot 2017	27	70	30	9	47%
Balmoral 2017	24	64	61	33	60%
Beausejour 2017	22	51	75	42	60%
Miami 2017	29	66	27	24	46%
Swan River 2017	32	43	51	39	53%
Melita 2017	11	79	9	38	55%
MacGregor 2017	32	79	34	22	58%
Riding Mountain 2017	48	66	91	19	83%
Long Plain 2017	27	70	30	9	47%
Dencross 2017	22	51	75	42	62%
Pansy 2017	29	54	36	10	40%
Dauphin 2017	48	66	91	19	83%
Long Plain 2018	22	110	39	19	71%
Haywood 2018	39	59	56	23	65%
Stonewall 2018	47	90	90	77	110%
Steinbach 2018	59	71	44	84	87%
Swan River 2018	60	113	76	47	105%

[a]Precipitation data from MPSG single page reports for each site-year
[b]Data not available for Long Plain 2017

3.3.4 Microplot Selection

Paired microplots were established in each on-farm field-scale strip trial at the R2 growth stage to investigate microscale responses to K fertilization. Samples from the microplots included soil and plant tissue samples at the R2 growth stage and harvest samples at maturity. Microplots were selected based on visual differences in growth and vigour identified at a small scale resulting from K fertilization. Approximately eight paired microplots were established within each field-scale trial; four in areas where the untreated soybeans looked as good or better, in growth and vigour, compared to the adjacent treated soybeans and four areas where the untreated soybeans looked inferior in growth and vigour compared to the adjacent treated soybeans. These visual differences were used as cues for selection of areas within the field-scale strip trial where STK was likely to vary, to investigate K responsiveness of soybean across a range of STK values. Targeted selection based on differences in growth and vigour resulting from K fertilization facilitated investigation of soybean K response and the relationship between response parameters at a detailed scale where response was likely. Each paired microplot area was approximately 6 m x 3 m, with two areas of approximately 3 m x 3 m for the treated and untreated microplot areas, respectively. The location of each microplot was identified using a handheld GPS.

3.3.5 Microplot Midseason Paired Soil and Plant Tissue Samples

Paired soil and plant tissue samples were taken from each site-year at the R2-3 growth stage. A 0-15 cm composite soil sample, comprised of four sub-samples, was taken from each control strip microplot area to determine STK in the control areas at the time of sampling. Soil samples were stored in a walk-in cooler at 4˚C until processing. To process, the samples were uniformly mixed, air-dried and ground with a high-speed pulveriser soil grinder, to duplicate common practice in commercial soil testing labs. Ammonium acetate exchangeable STK was determined using the Pratt (1965) method, with the inclusion of solution K in the quantification of exchangeable K. Five grams of dry soil were weighed into 50 mL centrifuge tubes to which 25 mL of neutral 1 M ammonium acetate extraction solution was added. Centrifuge tubes were placed horizontally and shaken for 5 minutes on a reciprocating shaker at 150 strokes per minute. Samples of extract were then filtered through Whatman No.1 filter paper, collected in scintillation vials and analyzed by Farmers Edge Laboratories (Winnipeg, MB) for K with a Thermo Scientific iCAP 6300 inductively coupled plasma optical emission spectrometer.

Tissue samples consisting of 25 uppermost mature trifoliate (UMT) leaves, each UMT including the three leaflets and petiole, were taken from the microplot in the control strip as well as from a microplot in the adjacent treated area for comparison of K concentration in the tissue. Plant tissue samples were air-dried for at least 48 hours to reduce moisture content, prior to oven drying in a forced-air oven at 60˚C for at least 24 hours. Once dry, the tissue samples were ground to pass through a 2 mm sieve using a Wiley Mill grinder. Samples were sent to Agvise Laboratories (Northwood, ND) for K analysis by digestion with a nitric acid/hydrogen peroxide cook down method, and then analyzed for K content with a Perkin Elmer ICP-OES 5400 inductively coupled plasma optical emission spectrometer.

3.3.6 Microplot Physiological Maturity Samples

Harvest samples were collected at maturity to determine yield and seed K concentration in the same microplots that were soil and tissue sampled earlier in the growing season. Whole plants were hand harvested from each microplot. For site-years with seed-row spacings less than 76 cm, 3-1 m x 2 row samples were collected and consolidated to give one composite harvest sample for each microplot area. For site-years planted on 76 cm row spacing, 3-1 m x 1 row samples were collected and consolidated to give one composite harvest sample for each microplot area. Samples were brought back to the University of Manitoba where they were air-dried for at least 48 hours prior to stationary threshing with a Wintersteiger Classic combine to isolate the seed. Immediately prior to threshing, each sample was weighed. After threshing, the seed from each sample was collected and stored for weighing and moisture content determination. Moisture content of the grain was determined using an MTC® Moisture Analyzer 999-FR in 2017 and a Labtronics® Model 919® Automatic Moisture Meter in 2018. Seed K concentration was measured, using the same method of analysis as for midseason tissue K discussed in section 3.3.4.

3.3.7 Field-Scale Strip Trial Yield

Field-scale strips were harvested at maturity by the producer, using a commercial, field-scale combine. Strip yield was determined using a weigh wagon, according to MPSG's on-farm trial harvest protocol. Strip yield data were collected for 19 of the 20 site-years, with no strip yield data collected for Long Plain 2017.

3.3.8 Statistical Analysis

Analysis of variance (ANOVA) for the paired microplots was conducted using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc 2018). for midseason paired tissue samples, paired seed and paired yield at physiological maturity. The same procedure was used for the ANOVA for strip yield data. In both experiments, site-year and treatment were fixed effects, while block (within site-year) was a random effect. Site-year was treated as a fixed effect, so that we could investigate site-year x treatment interactions and assess the effect of site-year conditions (e.g., soil test K concentration) on response to K fertilization. Assumptions of normality of the data were tested using Proc Univariate, with the data assumed to follow a normal distribution if the Shapiro-Wilk statistic was >0.90. Unequal variances with sites that may have had missing data were corrected for in the GLIMMIX procedure. Letter groupings were assigned to least square means (P<0.05) using the Tukey-Kramer test. Where regression analysis was used, Proc Reg was used to conduct the F test (P<0.05).

3.4 Results and Discussion

3.4.1 Seed Yield in Field-Scale Strip Trials

Although the ANOVA did not indicate a significant effect of K fertilizer treatment alone on seed yield for all of the field-scale strip trials, there was a significant site-year x treatment interaction, indicating the effect of K fertilization on seed yield was not consistent across site-years (Table 3.3). Three site-years had significant differences between control and treatment strip yield: Melita 2017 and Long Plain 2018 had increases in yield with K fertilization, while Swan River 2017 had a significant decrease in yield in strips with added K fertilizer compared to control strips with no added K. The reasons for this decrease in yield are not known. Complete tissue analysis of composite samples from microplot control and treated areas did not reveal any deficiencies or toxicities of concern (e.g., Cl^- toxicity) (Appendix III). The two sites where K fertilization increased yield, Melita 2017 and Long Plain 2018, had background STK concentrations on either side of MB's current 100 mg kg^{-1} threshold for recommending an application of added K, at 155 mg kg^{-1} and 76 mg kg^{-1}, respectively. Based on these site background concentrations and the current threshold, a yield response was anticipated at Long Plain 2018, but not Melita 2017.

Using the 100 mg kg^{-1} STK threshold as a predictor of yield response to K fertilizer, the frequency of yield response was less than expected across all 19 site-years that were harvested. There were six site-years that had STK concentrations below this threshold and a yield response to K fertilization was anticipated for these site-years. However, of these six site-years, only Long Plain 2018 had a significant yield increase with K fertilization. The relationship between STK and relative yield was expected to increase linearly to 100 mg kg^{-1}, after which a plateau was expected where the added K fertilizer would not provide a yield benefit. Therefore, regression analysis was conducted only on the data points with less than or equal to 100 mg kg^{-1} STK, since this is where a linear upward trend was anticipated. However, no upward linear trend is evident within this range of STK (Fig 3.1). This inconsistency of response at site-years classified as low or sufficient in K, according to the current threshold, suggests that ammonium acetate (NH_4OAc) STK was not a reliable indicator of soybean K response for these site-years and/or the 100 mg kg^{-1} threshold is too high for soybean in MB.

Table 3.3 Soybean seed yield for control and K fertilized strips for field scale strip trials

Site-year	Treatment[a]	
	Control	+ K
	——— kg ha^{-1} ———	
Elm Creek 2017	2405*a*	2466*a*
Portage la Prairie 2017	2486*a*	2567*a*
St. Claude 2017	1819*a*	1745*a*
Bagot 2017	2641*a*	2668*a*
Balmoral 2017	1671*a*	1698*a*
Beausejour 2017	1192*a*	1307*a*
Dencross 2017	1489*a*	1367*a*
Miami 2017	2614*a*	2526*a*
Swan River 2017	3038*a*	2762*b*
Melita 2017	3052*b*	3200*a*
MacGregor 2017	2243*a*	2203*a*
Riding Mountain 2017	2567*a*	2594*a*
Dauphin 2017	1987*a*	2007*a*
Pansy 2017	1199*a*	1219*a*
Long Plain 2018	2479*b*	2809*a*
Haywood 2018	2162*a*	2095*a*
Stonewall 2018	2991*a*	2984*a*
Steinbach 2018	2674*a*	2721*a*
Swan River 2018	3308*a*	3281*a*
ANOVA	df	*Pr>F*
Treatment	1	0.5
Site-year	19	<0.0001*
Site-year*Treatment	19	0.0008*
Coeff Var (C.V.)		27

*Significant at $P<0.05$

[a]Means within rows that are followed by the same letter are not significantly different ($P<0.05$)

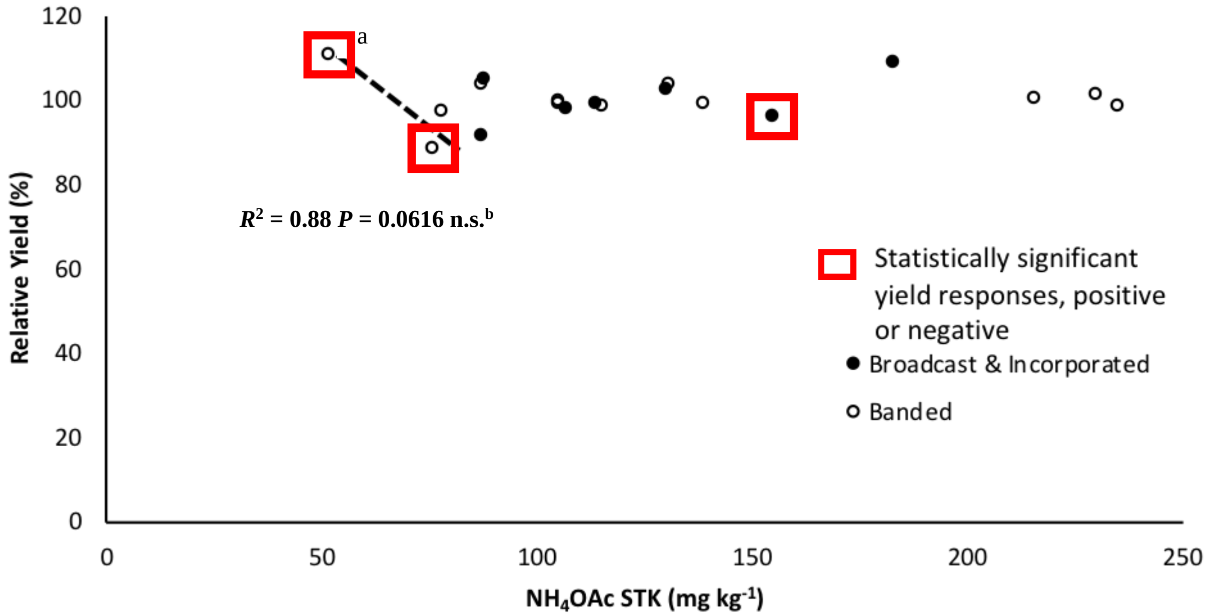

Figure 3.1 Relative yield response to K fertilization for soybean (control as % of fertilized) in relationship to site background ammonium acetate soil test K (STK) concentrations in field-scale strip trials

[a]The site background STK concentration of 52 mg kg^{-1} was determined in the fall, prior to establishing the trial. Estimated site STK from a composite sample taken at midseason sample timing from untreated strips during the trial was 163 mg kg^{-1}
[b]The R^2 value and P-value describe the regression between STK and relative yield for the data points less than or equal to 100 ppm STK

Site-years with a wide range in background STK concentrations were used in this study to investigate the validity of MB's current 100 mg kg^{-1} threshold for soybean and to determine if it needed to be raised or lowered. Given the low frequency of soybean yield response to K fertilization, and the lack of an agronomically meaningful relationship between site background STK concentrations below the 100 mg kg^{-1} threshold and relative yield, no recommendation as to the validity of the current threshold or possible necessary adjustments of the value can be made. Furthermore, the data calls into question the validity of NH_4OAc STK as a predictor of yield response for soybean at these site-years.

3.4.2 Microplot Tissue K, Seed Yield and Soil Test K

The locations of paired microplots were selected based on visual differences in growth and vigour between adjacent treated and untreated strips. The original intention was to establish microplot areas based on the presence of visual K deficiency symptoms, focusing on K response and relationship of response with yield predictors in these areas of the field-scale trial where K response was likely. However, at the time of microplot selection, which was based on the growth stage for tissue sampling to determine K concentration in the soybean tissue, no visual K deficiency symptoms were present. Therefore, paired microplots were selected based on other visual differences in growth such as colour, plant height and vigour.

The ANOVA indicated that K fertilization generally increased the concentration of UMT K in the treated microplots compared to the untreated microplots (Table 3.4). However, the magnitude of UMT K increase varied among site-years, resulting in a significant site-year x treatment interaction. Significant differences in UMT K concentration between treatments occurred at Portage la Prairie 2017, Beausejour 2017, Long Plain 2017 and Long Plain 2018, with K fertilization increasing UMT K concentration in microplots at each of these site-years. Although only these four increases were significant when analyzed by site-year, the overall treatment effect in the global ANOVA indicates that soybean in these areas of the treatment strips were generally taking up some fertilizer K; however, the effect of K fertilizer on tissue K concentration in the microplots might not be transferable to a field-scale. Due to the nature of microplot establishment with locations selected where positive or negative responses to K seemed likely, the effect of K fertilization at a microplot scale would not necessarily be expected to reflect the overall response for the field-scale strips. Rather, the microplots were utilized to investigate soybean K response parameters at a detailed scale, within the strips.

Table 3.4 Midseason uppermost mature trifoliate tissue K in soybean from control and K fertilized microplots within field-scale strip trials

Site-year	Treatment[a]		
	Control	+ K	n[b]
	——— mg kg^{-1} ———		
Elm Creek 2017	20.6*a*	21.9*a*	8
Portage la Prairie 2017	18.0*b*	20.1*a*	7
St. Claude 2017	20.0*a*	19.9*a*	8
Bagot 2017	19.0*a*	19.4*a*	8
Balmoral 2017	19.4*a*	20.3*a*	8
Beausejour 2017	15.8*b*	17.3*a*	8
Miami 2017	20.8*a*	20.1*a*	8
Swan River 2017	22.1*a*	21.1*a*	8
Melita 2017	20.3*a*	21.5*a*	8
MacGregor 2017	20.6*a*	22.0*a*	8
Riding Mountain 2017	22.4*a*	23.3*a*	8
Dauphin 2017	24.5*a*	25.3*a*	8
Long Plain 2017	17.6*b*	19.9*a*	8
Dencross 2017	21.8*a*	21.7*a*	8
Pansy 2017	17.8*a*	18.2*a*	8
Haywood 2018	17.4*a*	17.9*a*	8
Stonewall 2018	17.2*a*	17.5*a*	6
Steinbach 2018	17.9*a*	18.3*a*	8
Swan River 2018	16.9*a*	16.9*a*	8
Long Plain 2018	16.4*b*	18.7*a*	8
ANOVA	Df	*Pr>F*	
Treatment	1	<0.0001*	
Site-year	19	<0.0001*	
Site-year*Treatment	19	0.0221*	
Coeff Var (C.V.)		15	

*Significant at $P<0.05$

[a]Means within rows that are followed by the same letter are not significantly different ($P<0.05$)

[b]These n values represent the number of microplot pairs sampled at each site-year

Comparing the midseason UMT K concentrations with the critical K concentration range of 15.6 to 19.9 g kg^{-1} established in Iowa by Stammer and Mallarino (2018), UMT K was in or below the critical range in the control treatments at all sites in 2018, as well as Portage la Prairie 2017, Bagot 2017, Balmoral 2017, Beausejour 2017 and Long Plain 2017. Although four site-years had significant increases in UMT K concentration in treated microplots compared to control microplots, only the increase at Portage la Prairie 2017 raised the UMT K concentration above the critical range. At the other site-years where control UMT K was in the critical range, K fertilization still generally increased K concentration, but these increases were not statistically significant on an individual site-year basis. So, generally, there is evidence that some of the added K fertilizer was taken up by the soybean, but this increase in treated microplots was not always sufficient to raise the UMT K concentration above the critical range. This indicates the threat of K deficiency was still present at some site-years, in the microplots, at the R2 growth stage when tissue samples were collected, even with K fertilization.

Midseason STK values for the untreated microplots, determined at tissue sample timing, were highly variable between microplots at several locations, indicated by the large CV values (Table 3.5). Although the microplots were not selected randomly, the CV values from the STK of the microplots still indicate the large variability in STK concentrations that can exist within a field. These large CV values demonstrate the challenge of characterizing overall K fertility status and K response in commercial fields where variability is often large.

Analysis of variance showed a significant overall increase in seed yield from K fertilization in the microplots and also revealed a significant site-year x treatment interaction, indicating that the magnitude of K fertilization effect on seed yield varied among site-years (Table 3.6). Significant seed yield differences between treated and untreated microplots were found at only two site-years, St. Claude 2017 and Riding Mountain 2017; however, seed yield was measured in only four pairs of microplots at Riding Mountain 2017. The seed yield increases at these two site-years were not expected, given that St. Claude 2017 and Riding Mountain 2017 did not have statistically significant differences in midseason tissue K concentration between fertilized and unfertilized microplots. These findings contrast with Clover and Mallarino (2013) who found significant seed yield increases with K fertilization only where significant increases in tissue K concentration were detected midseason, but, that an increase in K concentration in the tissue did not always indicate that a yield response to K addition would occur. An increase in tissue K concentration without an increase in seed yield could be a result of luxury consumption (Clover and Mallarino 2013). However, examining the tissue K concentrations of the treated and untreated microplots for Portage la Prairie 2017, Beausejour 2017, Long Plain 2017 and Long Plain 2018, there is little evidence of luxury consumption. Potassium concentrations are within or just above critical range concentrations for the treated microplots in each of these three site-years where significant tissue responses occurred.

Examining the relationship between midseason STK concentrations and relative yield for the untreated vs. treated pairs of microplots, the differences in STK do not explain the differences in relative yield (Fig 3.2). A significant linear upward trend was expected for the pairs of microplots where the control treatments' STK concentrations were less than 100 mg kg^{-1}, that is, those microplots where STK was below the current threshold for recommending an application of added K fertilizer. However, there was no such relationship. As with the field-scale strip yield data, this suggests STK is not well related to relative yield in soybean and is not, therefore, a good predictor of yield response to K fertilization for these site-years and/or the 100 mg kg^{-1} threshold is too high for soybean in MB.

Table 3.5 Midseason soil test K variability for untreated microplots within field-scale strip trials

Site-year	CV (%)	*n*[a]
Beausejour 2017	16	8
Elm Creek 2017	31	8
Portage la Prairie 2017	17	7
St. Claude 2017	16	8
Bagot 2017	70	8
Balmoral 2017	42	8
Miami 2017	28	8
Pansy 2017	5	8
Swan River 2017	43	8
Melita 2017	23	8
MacGregor 2017	12	8
Riding Mountain 2017	40	8
Dauphin 2017	16	8
Dencross 2017	45	8
Long Plain 2017	20	8
Long Plain 2018	32	8
Haywood 2018	13	8
Stonewall 2018	12	6
Steinbach 2018	71	8
Swan River 2018	21	8

[a]These *n* values represent the number of microplot pairs sampled at each site-year

Table 3.6 Soybean seed yields for paired microplots within field-scale strip trials

Site-year	Treatment[a]		
	Control	+ K	n[b]
	——— kg ha^{-1} ———		
Elm Creek 2017	2385*a*	2418*a*	8
Portage la Prairie 2017	1462*a*	1374*a*	7
St. Claude 2017	1900*b*	2897*a*	8
Bagot 2017	1388*a*	1455*a*	8
Balmoral 2017	889*a*	889*a*	8
Miami 2017	1374*a*	1367*a*	8
Swan River 2017	1617*a*	1543*a*	8
Melita 2017	1650*a*	1758*a*	8
MacGregor 2017	1489*a*	1415*a*	8
Riding Mountain 2017	1361*b*	1758*a*	4
Dauphin 2017	1428*a*	1307*a*	8
Long Plain 2017	1792*a*	1873*a*	8
Beausejour 2017	620*a*	802*a*	8
Pansy 2017	1138*a*	1085*a*	8
Dencross 2017	805*a*	729*a*	6
Long Plain 2018	1058*a*	1145*a*	8
Haywood 2018	1044*a*	1118*a*	8
Stonewall 2018	1495*a*	1536*a*	6
Steinbach 2018	1495*a*	1751*a*	8
Swan River 2018	1415*a*	1354*a*	8
ANOVA	df	*Pr>F*	
Treatment	1	0.0083*	
Site-year	19	<0.0001*	
Site-year*Treatment	19	<0.0001*	
Coeff Var (C.V.)		35	

*Significant at $P<0.05$

[a]Means within rows that are followed by the same letter are not significantly different ($P<0.05$)

[b]These n values represent the number of microplot pairs sampled at each site-year

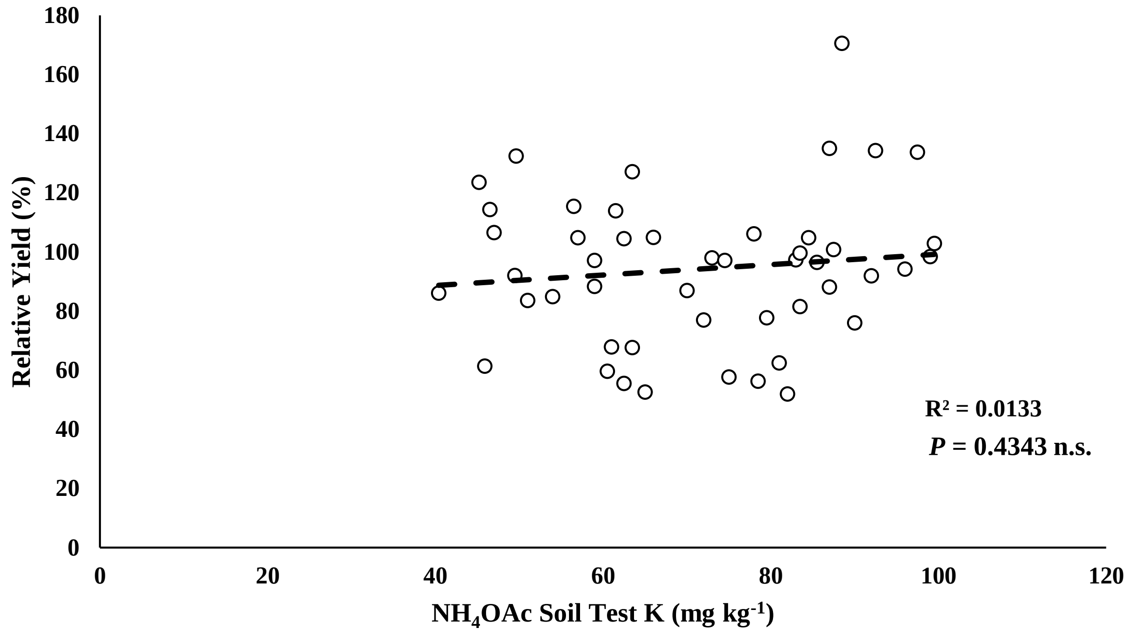

Figure 3.2 Relationship between microplot ammonium acetate soil test K (STK) and relative yield (untreated control as percent of fertilized) for soil test K values <100 mg kg^{-1}

Generally, K fertilization increased the concentration of K in microplot soybean seed (Table 3.7). However, the magnitude of increase in seed K was not consistent across site-years, resulting in a site-year x treatment interaction. Potassium fertilization increased seed K significantly at three sites, Elm Creek 2017, St. Claude 2017 and Long Plain 2018, but decreased seed K at Riding Mountain 2017. However, as mentioned previously, soybean seed was harvested at only four pairs of treated and untreated microplots at Riding Mountain 2017. Using the critical soybean seed K concentration range of 14.6 -16.2 g kg^{-1} established from Canadian studies by Parvej et al. (2016) to diagnose K deficiency post-season, all site-years had seed K concentrations above this critical range. Thus, despite indications of deficiency at midseason, with several site-years' tissue K concentrations in or below the critical range, by the end of the season that threat of deficiency was generally not reflected in seed K concentrations, which indicated that K fertility for soybean seed yield was sufficient in the microplots at every site-year.

Table 3.7 Microplot seed K concentration for soybeans in paired microplots within field-scale strip trials

Site-year[a]	Treatment[b]	
	Control	+ K
	——— mg kg^{-1} ———	
Elm Creek 2017	18.1*b*	18.9*a*
Portage la Prairie 2017	17.1*a*	17.4*a*
St. Claude 2017	17.3*b*	18.0*a*
Bagot 2017	17.3*a*	17.7*a*
Balmoral 2017	18.0*a*	18.0*a*
Beausejour 2017	18.0*a*	18.0*a*
Miami 2017	18.8*a*	18.4*a*
Swan River 2017	18.8*a*	19.0*a*
Melita 2017	17.8*a*	18.0*a*
Riding Mountain 2017	18.5*a*	17.5*b*
Dauphin 2017	18.0*a*	18.4*a*
Long Plain 2017	19.3*a*	19.4*a*
Pansy 2017	17.8*a*	18.2*a*
Dencross 2017	21.8*a*	21.7*a*
Long Plain 2018	16.4*b*	18.7*a*
Haywood 2018	17.4*a*	17.9*a*
Stonewall 2018	17.2*a*	17.5*a*
Steinbach 2018	17.9*a*	18.3*a*
Swan River 2018	16.9*a*	16.9*a*
ANOVA	df	*Pr>F*
Treatment	1	0.0013*
Site-year	18	<0.0001*
Site-year*Treatment	18	0.0017*
Coeff Var (C.V.)		7

*Significant at $P<0.05$
[a]Data not available for MacGregor 2017
[b]Means within rows that are followed by the same letter are not significantly different ($P<0.05$)

Overall, soybean seed yield response to K fertilization within the pairs of microplots was not reliably predicted by STK concentration, midseason tissue tests, or seed K concentration. Furthermore, responses in any one of these parameters were not consistently associated with responses in the others. The lack of yield response could have been related to the below-average growing season precipitation at the majority of the site-years (Table 3.2). Lack of adequate rainfall during the growing season could have a twofold effect on the lack of K responsiveness of soybean, affecting both K movement in the soil and yield potential of the soybeans. Since K moves via diffusion in the soil, moisture conditions are very important for facilitating movement of fertilizer K to soybean roots for uptake. Additionally, reduced soybean yield potential probably resulted from the inadequate growing season precipitation at most site-years. The disappearance of suboptimal plant K concentrations between midseason (UMT tissue K) and harvest (seed K) could have been the result of the declining yield potential due to drought stress, resulting in less demand for K uptake by the plants.

The inconsistent and infrequent soybean yield responses to K fertilization, accompanied by the lack of a significant relationship between STK concentration and relative yield do not enable robust evaluation of 100 mg kg^{-1} as the critical threshold for recommending application of K fertilizer to soybean. Furthermore, as with the field-scale results, the validity of the NH_4OAc test to predict soybean yield response to K fertilization is called into question.

3.4.3 Overall Discussion

Soybean seed yield response to K fertilization was infrequent and unrelated to background STK concentrations at both field and microplot scales. The microplots highlighted the variability in STK that exists within a field. The method of establishing microplots based on differences in visual cues of growth and vigour relied on that variability to be present and the large CV values for microplot STK concentrations within each site-year illustrate the variability.

Uppermost mature trifoliate K concentration at the R2 growth stage was an unreliable predictor of whether microplot soybean seed yield or seed K concentration responses to K fertilization would occur. Four site-years had significant increases in microplot UMT K concentration with K fertilization but none of these site-years had a significant increase in microplot seed yield or seed K concentration. Additionally, of the four site-years where K fertilization raised UMT K concentrations, K fertilization raised the UMT K concentration above the critical range at only one site-year. This indicates that at the R2 growth stage, the threat of K deficiency was present at several site-years. However, by the end of the season, the threat of deficiency had generally diminished, since all site-years had seed K concentrations above the critical range for both control and K fertilized microplots. The shift from potential deficiency to sufficiency in K nutrition over the course of the growing season was likely due to inadequate growing season precipitation and a decline in yield potential.

3.5 Conclusions

The challenge of characterizing K response of soybean and predicting where response to K fertilization will occur did not become easier with a large, field scale strip trial approach or a magnified, detailed approach. Both of these approaches call into question the validity of the NH_4OAc test and the 100 mg kg^{-1} threshold to guide K fertilization decisions for soybean in MB and predict where yield response to K fertilization will occur. Due to the low frequency of yield response and lack of relationship between STK and relative yield, the threshold for recommending an application could not be evaluated. Further research is needed to investigate the extent of yield loss that is present in soybeans that do show K deficiency symptoms. Additionally, a better predictive tool for soybean K response is required to help guide K fertility management decisions for soybean in MB.

3.6 References

Bowman, B.T. 1994. A literature review of on-farm research design and data evaluation methods.[Online] Available: https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/15000/GP_rep2_1.pdf?sequence=1&isAllowed=y [8 May 2019].

Clover, M.W., and Mallarino, A.P. 2013. Corn and soybean tissue potassium content responses to potassium fertilization and relationships with grain yield. Soil Sci. Soc. Am. J. **77**: 630–642.

Cook, S.E., and Bramley, R.G.V. 2000. Coping with variability in agricultural production - Implications for soil testing and fertiliser management. Commun. Soil Sci. Plant Anal. **31**: 1531–1551.

Franzen, D.W. 2018. North Dakota fertilizer recommendation tables and equations. [Online] Available: https://www.ag.ndsu.edu/publications/crops/north-dakota-fertilizer-recommendation-tables-and-equations/sf882.pdf [8 May 2019].

Franzen, D.W., and Peck, T.R. 1997. Spatial variability of plant analysis potassium levels. Commun. Soil Sci. Plant Anal. **28**: 1081–1091.

Iowa Soybean Association. 2016. Guide to on-farm replicated srip trials 2016. [Online] Available: https://www.iasoybeans.com/upl/downloads/publications/a-farmer-s-guide-to-replicated-strip-trials-2016.pdf [7 May 2019].

Kaiser, D.E. 2018. Soybean fertilizer recommendations. [Online] Available: https://extension.umn.edu/crop-specific-needs/soybean-fertilizer-recommendations#phosphate-and-potash-1078561 [8 May 2019].

Manitoba Agriculture. 2019. Yield Manitoba. [Online] Available: https://www.masc.mb.ca/masc.nsf/ym_2019_full_issue.pdf [10 June 2020].

Manitoba Pulse and Soybean Growers (MPSG). 2018. Water limitations in pulse and soybean crops. [Online] Available: https://www.manitobapulse.ca/2018/06/water-limitations-in-pulse-and-soybean-crops/ [6 Aug. 2019].

Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). 2017. Agronomy guide for field crops. [Online] Available: http://www.omafra.gov.on.ca/english/crops/pub811/pub811.pdf [8 May 2019].

Parvej, M.R., Slaton, N.A., Fryer, M.S., Roberts, T.L. and Purcell, L.C. 2016b. Postseason diagnosis of potassium deficiency in soybean using seed potassium concentration. Soil Sci. Soc. Am. J. **80**: 1231.

Pratt, P.F. 1965. Potassium. Pages 1022–1030 *in* Methods of Soil Analysis. Amer. Soc. Agron., Madison, WI.

SAS Institute. 2018. The SAS system for Windows. Release 9.4. SAS Inst., Cary, NC.

Sawchik, J., and Mallarino, A.P. 2007. Evaluation of zone soil sampling approaches for phosphorus and potassium based on corn and soybean response to fertilization. Agron. J. **99**: 1564–1578.

Stammer, A.J., and Mallarino, A.P. 2018. Plant tissue analysis to assess phosphorus and potassium nutritional status of corn and soybean. Soil Sci. Soc. Am. J. **82**: 260–270.

4. SYNTHESIS

Given the expansion of soybean production in Manitoba (MB) in recent years, the high rate of potassium (K) removal for soybean and the lack of comprehensive historical K fertility research in MB specific to soybean, the objective of this study was to investigate K fertility and fertilizer response of soybean in MB. This investigation was focused on two main objectives: investigating the frequency of soybean yield response to K fertilization across a range of background ammonium acetate soil test K (STK) concentrations and determining the K fertilizer rate and placement combination best suited to increasing soybean seed yield. To meet these two objectives, our study also investigated the relationship between STK and relative yield, facilitating evaluation of the current 100 mg kg^{-1} threshold for recommending an application of K fertilizer on soybean.

4.1 Outcomes Across Spatial Scales

The investigation of K fertility and fertilizer response of soybean in our study involved three spatial scales: small plot, on-farm field-scale, and paired microplots within field-scale trials. Across the scales of investigation, some similar outcomes reinforced the following concepts: spatial distribution of STK was highly variable; K nutrition status in soybean was temporally variable; STK and relative yield were not related and the 100 mg kg^{-1} STK threshold failed to predict soybean yield response to K fertilization.

Spatial variability in STK concentrations at a small plot scale created a challenge in comparing the efficacy of K fertilizer rate and placement combinations; with high variability across the site area, STK was not consistent among plots within a site-year. Similarly, within field-scale trials, microplot STK concentrations for similar treatments had very high CVs in most cases, indicating high variability in STK among microplots within a field-scale site-year. This in-field variability probably results in patches where yield response in small plots and paired microplots may differ from overall response at a field-scale.

In addition to the spatial variability in STK, K nutrition status of the soybean plants was temporally variable within the growing season. At both the small plot and microplot scale, the sufficiency of plant K status changed from midseason tissue sampling to end of season seed sampling. In most cases, a threat of deficiency was present midseason, as indicated by tissue K concentrations within or below the established critical range; however, by the end of the season for all microplots and almost all small plots, this threat of deficiency had shifted to sufficient K nutrition status indicated by seed K concentration being above the critical range. In our study, this temporal shift in K nutrition status may have resulted from declining yield potential over the growing season, as moisture became increasingly limiting at the majority of site-years.

Spatial variability in STK and temporal variability in crop K nutrition status presented challenges in quantifying the potential benefits of adequate K fertilization in-field. The lack of a statistically significant or agronomically meaningful relationship between STK and relative yield was consistent across small plot, on-farm and microplot results and calls into question the efficacy of the ammonium acetate (NH_4OAc) test for making K fertilizer recommendations for soybean in MB. Additionally, perhaps as a by-product of this lack of relationship, the 100 mg kg^{-1} threshold for recommending an application of K fertilizer to soybean did not reliably predict yield response to K fertilization. Such spatial and temporal variability challenges the isolation of treatment effects on yield, and the difficulty in characterizing yield response is further complicated by the lack of adequate predictors for where and when yield response will take place. The similar findings regarding spatial and temporal variability across the three spatial scales of investigation highlight the difficulty of characterizing soybean yield response to K fertilization in MB.

The frequency of yield response varied depending on the spatial scale of investigation. At a small plot scale where variability in STK from plot to plot within a site-year was high, there was no seed yield response to K fertilization. However, in the on-farm field scale research trials, where in-field variability was accommodated by the large area within each strip, variability across replicates was much less and there were two site-years with soybean seed yield increases in response to K fertilization. Similarly, there were two site-years with seed yield increases in the paired microplots, albeit at different locations and for a different reason than the decreased variability across replicates for the field scale strips. Due to the use of visual differences to select microplots, the response at field scale was not anticipated to reflect response at a microplot scale. Unlike at field scale where the K fertilizer effect is determined across all the variability that may exist within each strip, investigation of microplot response created the opportunity to determine the variability of soybean response to K fertilization within the strips. By isolating small-scale areas within the field-scale strips where soybean K response seemed likely, the background variability that probably masked the ability to determine potential yield response at a small plot scale was at least partially overcome. By incorporating more than small plot scale investigation, alone, we determined that there is the potential for soybean to respond to K fertilization in MB; however, the difficulty is reliably characterizing when and where response is likely.

4.2 Implications for Farmers

Potassium fertility management is especially a concern for farmers in areas with coarse textured soils in MB that may be inherently low in K. Although predicting soybean K response is unreliable using the current available method of the NH_4OAc test and relying on the 100 mg kg^{-1} threshold, soybean is still a crop that consumes and exports a large amount of K. With soybean in the crop rotation, maintaining K fertility in the soil to support K nutrition for all crops in the rotation (e.g., barley, which responded to K fertilization at our small plot sites in 2018 where soybean did not) is important. A possible method for crop production on soils with low to marginally sufficient STK, could be to manage K fertility across the crop rotation, balancing inputs and exports from the system across the whole rotation.

4.3 Next Steps for Manitoba Soybean Potassium Fertility Research

There are several next steps necessary to better understand K fertility for soybean in MB. The immediate need is to better understand the fundamental processes governing soil K dynamics, availability and ultimately soybean K nutrition from soil K. This would facilitate selection of an existing soil test, or development of a new test, better suited to predicting soybean response to K fertilization. Given the inefficacy of the NH_4OAc test and current 100 mg kg^{-1} threshold for predicting soybean yield response to K fertilization, there may be merit to investigating crop-specific thresholds and recommendations for K fertility. A secondary study conducted in 2018, in response to the first year of data from our study, compared soybean responsiveness to K fertilization to barley, a crop historically known to respond well to K fertilization in MB. The results indicated a yield increase for barley with K fertilization but no yield response for soybean; perhaps the NH_4OAc test, which works well to predict yield response in some crops such as barley, is not suitable for predicting soybean yield response in MB. However, prior to assessing different types of soil tests for guiding soybean K fertility recommendations in MB, deeper investigation of the dynamics of K within the soil would be informative. Bioavailable K is comprised of both exchangeable and nonexchangeable K, but generally, soil tests such as NH_4OAc only characterize the exchangeable K pool. Understanding the dynamic shifts between the exchangeable and nonexchangeable pools of K over the course of a growing season could provide beneficial information about how much the nonexchangeable K pool contributes to crop K nutrition. Inclusion of PRS probe K supply rates are useful for determining relative potential K bioavailability between site-years. They may play an important role in understanding soil K dynamics and the effect of different soil and environmental conditions on those dynamics. Additionally, investigation of the physiological factors that may facilitate greater extraction of soil K by soybean than for other crops would also inform future soil testing criteria needed to most accurately characterize K fertility and fertilizer response for soybean in MB.

In addition to the possibility that a different test would provide soil test K concentrations that are better related to soybean yield response, there is also the possibility that the current STK threshold of 100 mg kg^{-1} is too high for soybean. This would be surprising, given that thresholds in neighbouring soybean producing areas such as North Dakota, Minnesota and Ontario are all greater than MB's current threshold. However, it is possible that the current threshold for MB soils is simply too high. If this were the case, future research would need to include a substantial number of soils with substantially less than 100 mg kg^{-1} STK to re-investigate the frequency of soybean response to K.

Once the fundamental understanding of the soil related factors driving soybean K nutrition and a soil test method that can reliably predict K response of soybean are in place, the practical aspects of soybean yield response due to inadequate K nutrition can be characterized and the best strategies to mitigate those losses can be determined. Potassium concentration in uppermost mature trifoliate (UMT) leaves midseason, seed yield and seed K concentration at harvest are useful indicators of soybean K nutrition status and can indicate shifts in nutrition status over time. Uppermost mature trifoliate sampling is more efficient and less destructive than both whole plant and stem sampling, and since patterns of response were similar across all three types of tissue samples, UMT sampling may be the preferred method of midseason tissue analysis for future research.

On-farm, there are both agronomic and economic driving factors governing management of crop nutrition. From a practical perspective, characterizing the extent of soybean yield loss from low or marginally sufficient K fertility is important for economic decision making of K fertility management. One of the challenges with managing K fertility at a field scale is how patchy it can be across a field. Quantifying how much yield loss occurs in those patches, and the potential economic consequences of that loss, is important for decision making at a whole field or farm level. Just as important as characterizing the extent of loss from inadequate soybean K nutrition is determining the best K fertilization strategies to mitigate that loss. This could include re-investigation of soybean response to K fertilizer rate and placement combinations once soybean K response can be more reliably predicted, as well as investigating the implications of agronomic strategies such as managing K fertility across the crop rotation with a longer term K balance approach.

Soybean has become a prominent crop in MB's rotations. Being a large exporter of K from the soil and having identified there is potential for yield response to K fertilization, further investigation into the fundamentals and practical economics and agronomics for K management with soybean in the crop rotation will continue to be important.

5. APPENDICES

Appendix I

Table 1.1 Rate, placement and timing baseline fertilizer applied to small plot trials for each field season

Year	Fertilizer*	Rate of Nutrient	Placement	Timing
		——kg ha^{-1} ——		
2017	Monoammonium phosphate	60 P_2O_5	Sideband	Planting
	Ammonium Sulphate	20 S	Broadcast and incorporated	Spring pre-plant
	Copper Sulphate	4 Cu	Broadcast and incorporated	Spring pre-plant
	Zinc Sulphate	6 Zn	Broadcast and Incorporated	Spring pre-plant
2018	Monoammonium phosphate	60 P_2O_5	Sidebanded	Planting
	Ammonium Sulphate	49 S	Broadcast	In-season
	Agrotain® treated urea granules**	112 N	Broadcast	In-season

*Applied to all sites within a year unless otherwise noted
**Applied only to Haywood 2018 in response to a nodulation failure

Table 1.2 Glyphosate application timing and rate for soybean small plot site-years

Date*	Crop Stage	Rate
		——L ha^{-1} ——
05/30/17	VE	1.65
06/20/17**	V4	1.65
06/26/17***	V4	1.65
07/07/17	R1	1.65
06/01/18	V2	1.65
06/19/18	V4	1.65

*Applied at each site within a year on this date unless otherwise indicated
**Applied only at Haywood, St. Claude and Portage la Prairie
***Applied only at Elm Creek

Appendix II

Table 2.1 Small plot whole plant dry matter yield at growth stage V5/R2

Treatment[a]	Site-year							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot	All Sites
	2017	2017	2017	2017	2018	2018	2018	2017-2018
				—————— kg ha^{-1} ——————				
0 kg K_2O ha^{-1}	906	662	560	764	734	977	1092	814
33 kg K_2O ha^{-1} SB	939	576	554	774	816	992	1277	847
66 kg K_2O ha^{-1} SB	905	601	565	737	810	975	1245	834
33 kg K_2O ha^{-1} BI	936	548	501	763	789	1005	1068	801
66 kg K_2O ha^{-1} BI	900	610	571	764	641	953	1054	785
132 kg K_2O ha^{-1} BI	864	512	536	673	726	878	1084	753
Site-year Average[b]	908*abc*	585*cd*	548*d*	746*bcd*	753*bcd*	963*ab*	1137*a*	
ANOVA		df		*Pr>F*				
Trt		5		0.4642				
Siteyr		6		0.0109*				
Siteyr*Trt		30		0.9811				
Coeff Var (C.V.)				30				

*significant at $P<0.05$

[a]SB indicates sidebanded treatment, BI indicates broadcast and incorporated treatment

[b]Means within rows that are followed by the same letter are not significantly different ($P<0.05$)

Appendix III

Table 3.1 Composite nutrient analysis in whole plant soybean tissue from control and treatment midseason microplots at Swan River 2017

	Total-N %	P %	K %	S %	Ca %	Mg %	Na %	Zn mg kg^{-1}	Fe mg kg^{-1}	Mn mg kg^{-1}	Cu mg kg^{-1}	B mg kg^{-1}	Cl %
Control	4.02	0.37	2.2	0.31	1.57	0.55	0.01	46	95	49	6	40	0.04
Treated	3.85	0.38	2.2	0.30	1.52	0.54	0.01	44	104	42	5	42	0.06

Figure 3.1 Variability in K deficiency symptoms at Long Plain 2018 small plot site-year

Appendix IV Barley Soybean Potassium Responsiveness Comparison Study

Background and Objectives

The 2018 barley [*Hordeum vulgare*] soybean [*Glycine max* (L.) Merr] potassium (K) responsiveness comparison study was developed as a result of the unexpected lack of soybean seed yield response to K fertilization in the 2017 soybean small plot trials. Given that the majority of the small plot site-years were on soils that would be classified as low in K, according to the Manitoba Soil Fertility Guide as well as recommendations from Ontario, North Dakota and Minnesota, soybean yield response to K fertilization was anticipated. However, there was no seed yield response to any K fertilizer treatment at any of the small plot site-years in 2017. Growing season precipitation in 2017 was lower than normal, with site-years receiving between 63-65% of normal precipitation, which certainly limited yield potential. A decreased yield potential results in a parallel decrease in nutrient requirements and it is possible that in a growing season with closer to normal precipitation, K fertilization could have increased seed yield in soybean. However, this is not the first time a high K consuming crop, grown on low K soil, has not responded to K fertilization. Historically, canola, which also consumes a large amount of K over the growing season, has not reliably responded with increased seed yield when fertilized with K (Soper 1971, Grant and Bailey 1993). Additionally, differences in K responsiveness of different crops has been observed historically in Manitoba (MB); seed yield of rape, which is also a high K consuming crop like soybean, did not respond to K addition at the same sites where barley did (Soper 1965).

Two alternative explanations for the lack of soybean yield response on low K soils were hypothesized: perhaps the soils were releasing more K over the course of the growing season than the amount anticipated with the traditional ammonium acetate (NH_4OAc) soil test for K (STK), or, perhaps soybean is more efficient at extracting K from the soil than other crops. In either case, the amount of bioavailable K for soybean would exceed the amount anticipated by the soil test, thereby reducing soybean's reliance on K fertilization to meet K nutrition needs.

To investigate these possibilities, an experiment was designed to compare the responsiveness of soybean to K fertilization on low K soils with the responsiveness of barley, a crop known historically to respond well to K fertilization in MB. One of two outcomes was anticipated: either a lack of K response in both crops or an increase in yield with K fertilization in barley but not soybean. The former would suggest the soil supply of bioavailable K is much greater than anticipated by STK, and the latter would suggest soybean may have more access to soil K than other crops such as barley.

Materials and Methods

Site Description, Characteristics

Three sites were established in 2018, located in the same fields as the 2018 soybean small plot trials discussed in Chapter 2: near Haywood, MB (49˚41'00" N, 98˚12'17" W), Long Plain, MB (49˚50'46" N, 98˚25'13" W) and Bagot, MB (49˚56'57" N, 98˚33'17" W). Site characterization soil samples were taken in the spring, prior to planting. Six soil cores per site area were taken, in a "W" pattern, to a depth of 15 cm. A site-composite sample was made from thorough mixing of the six cores. The samples were sent to Agvise Laboratories (Northwood, ND) for complete analysis to determine site background STK concentrations as well as the need for any additional background fertilization with other nutrients. Ideally, all three sites would have had less than 100 mg kg^{-1} STK to improve the likelihood of response to K fertilization. The sites near Long Plain and Bagot met that criterion; however, the site near Haywood had a STK concentration of 125 mg kg^{-1} (Table 4.1). Due to logistics and site availability, this site was still used despite being just over the 100 mg kg^{-1} threshold for recommending an application of K fertilizer.

Experimental Design and Treatments

A randomized complete block with a split-plot treatment design was used for each of the three sites. The main plot was crop (barley or soybean) and the sub-plot was fertilizer treatment (132 kg K_2O ha^{-1} broadcast and incorporated or 0 kg K_2O ha^{-1}) (Figure 4.1).

Soybean +K	**Soybean 0 K**	**Barley +K**	**Barley 0 K**
Barley 0 K	**Barley +K**	**Soybean 0 K**	**Soybean +K**
Soybean 0 K	**Soybean +K**	**Barley 0 K**	**Barley +K**
Barley +K	**Barley 0 K**	**Soybean +K**	**Soybean 0 K**

Figure 4.1 Schematic of plot and treatment design for barley soybean potassium responsiveness study sites

Table 4.1 Nutrients and pH from site characterization soil sample for each barley-soybean site					
Site	Soil Test Values[a]				
	N	P	K	S	pH
Haywood	11	20	125	11	5.8
Long Plain	20	45	67	9	5.5
Bagot	30	7	59	34	7.8

[a] 0-15 cm nitrate-N (kg ha^{-1}), Olsen extractable P (mg kg^{-1}), ammonium acetate exchangeable K (mg kg^{-1}), and sulphate-S (kg ha^{-1})

All K fertilization treatments were broadcast by hand and incorporated with two passes of a tandem disc tillage operation prior to planting. For soybean, Roundup Ready II variety DKB005-52 was planted to achieve a target plant stand of 370 500 plants ha^{-1}. Planting depth ranged from 0.64 to 1.3 cm depth, depending on moisture conditions at each site-year. A John Deere 1755 4-row precision planter was used, with rows spaced 76 cm apart. The soybean seed was treated with Acceleron® seed treatment, which contained Imidacloprid insecticide, Fluxapyroxad, Pyraclostrobin and Metalaxyl fungicides. The seed was also treated with Optimize® ST liquid inoculant. In addition to the inoculant on the seed, Cell-Tech™ liquid inoculant was applied in the seedrow through the liquid kit on the planter at a rate of approximately 190 L ha^{-1}. The soybean plots were planted on May 17th, 2018, the same day as the soybean small plot sites were planted. For barley, Conlon variety treated with Raxil Pro was seeded with an Allis Chalmers double-disc press drill, with rows at 17.8 cm spacing, to achieve a target plant stand of 253 plants m^{-2}. The barley was seeded to a depth of about 2.5 cm on May 22 at all three sites.

To address additional fertility needs according to the site spring composite soil sample analysis from AgVise Laboratories (Northwood, ND), phosphorus was applied as monoammonium phosphate (MAP, 11-52-0) through the seeder for barley at a rate of 52 kg MAP ha^{-1} and sidebanded through the planter for soybean at a rate of 115 kg MAP ha^{-1}. Nitrogen was broadcast on barley plots as SuperU after establishment, on June 5th, 2018, at a rate of 112 kg N ha^{-1}. Sulphur was also applied after establishment, on July 3rd, 2018, at a rate of 16.8 kg S ha^{-1} as ammonium sulphate to barley plots and 22.4 kg S ha^{-1} as ammonium sulphate to soybean plots.

Herbicide was applied for in-season weed control on an as-needed basis. Glyphosate was applied at 1.65 L ha^{-1} to soybean plots and MCPA+bromoxynil was applied at a rate of 1 L ha^{-1} to barley plots, except at Haywood which received application at a rate of 6 L ha^{-1} due to an error in calculation. Glyphosate was applied to the soybean plots on June 6, 2018 at each site. MCPA+bromoxynil was also applied at each site, except Long Plain, on June 6, 2018. No further herbicide applications were required.

Weather Conditions

The 2018 growing season had lower than average growing season precipitation, with 66-88% of normal rainfall measured at the weather stations closest to the barley-soybean study sites (Table 4.2). Due to the coarse textured soils at each of the three sites where this study was conducted, the low precipitation probably reduced the yield potential of both crops. Due to the diffusion-mediated movement of K in soils, lack of adequate moisture could have also reduced the movement of fertilizer and soil K in the soils as well.

Table 4.2 Average air temperature, total corn heat units (CHU), monthly and total precipitation for weather stations close to barley-soybean study sites

Weather Station[a] (growing season)	Average Air Temperature[b]	Precipitation						
		CHU_{Total}[b]	May	June	July	Aug	Sep.	Total
	˚C		mm					
Elm Creek (2018)	16.3	2760.5	29.1	70.1	40.8	22.3	65.2	227.5
Portage (2018)	15.8	2709.1	20.6	92.9	36.9	20.1	124.7	295.2

[a]The Elm Creek and Portage weather stations were the closest available Manitoba Agriculture weather stations with data available from the Manitoba Agriculture Daily Weather Report (https://web43.gov.mb.ca/climate/DailyReport.aspx)
[b]Average air temperature and total CHU are from May 17 – Oct 18 for Elm Creek (2018) and May 17 – Oct 19 for Portage (2018)

Soil Measurements

In addition to the site characterization samples collected prior to trial establishment, within a week of planting, 0-15 and 15-30 cm soil samples were collected from every control plot at each site to characterize STK within the trial in more detail. The composite sample for each control plot was composed of ten cores at each depth. Samples were placed in plastic bags and stored in a walk-in cooler at 4˚C until sample processing. At the time of processing, each sample was mixed thoroughly in the bag, prior to spreading the sample on kraft paper and setting the sample on trays to dry at room temperature for 48 hours. After drying, the samples were ground with a high-speed pulveriser soil grinder.

Ammonium acetate exchangeable soil test K was determined using the method of Pratt (1965) and solution K was included in exchangeable K determination. Five grams of dried soil were weighed into 50 mL centrifuge tubes. Twenty-five mL of neutral 1 M NH_4OAc extraction solution were added and shaken for 5 minutes on a reciprocating shaker at 150 strokes per minute. Samples were then filtered through Whatman No.1 filter paper, collected in scintillation vials and analyzed by Farmers Edge Laboratories (Winnipeg, MB) for K, Ca, Mg and Na using a Thermo Scientific iCAP 6300 inductively coupled plasma optical emission spectrometer.

Tissue Measurements

Tissue samples were collected from each soybean and barley plot to determine if K fertilization increased K concentration in plant tissue and whether this change in concentration was influenced by crop type. Tissue samples were collected at the R2 growth stage of soybean, which corresponded approximately with barley anthesis. Twenty-five uppermost mature trifoliate leaves were collected from each soybean plot and 80 uppermost leaves were collected from each barley plot. Samples were collected in mesh bags, and air dried for at least 48 hours to reduce moisture content. Following air-drying, samples were oven-dried in a forced air oven for at least 24 hours at 60˚C. The oven-dry mass was taken and then samples were ground to pass through a 2 mm sieve using a Wiley Mill grinder. Samples were sent to Agvise Laboratories (Northwood, ND) for K analysis by digestion with a nitric acid/hydrogen peroxide cook down method, and then analyzed for K content with a Perkin Elmer 5400 ICP-OES.

Harvest Measurements

At maturity, a 3 m x 4 row area from the centre of each barley plot was harvested by hand. Samples were collected in mesh bags and dried at room temperature for approximately one week. Samples were processed through a Wintersteiger Classic plot combine to obtain yield and moisture content data using the combine’s HarvestMaster® Classic GrainGage system. At soybean maturity, the centre two rows from each 8 m soybean plot were harvested using the same Wintersteiger Classic plot combine. The combine's HarvestMaster® Classic GrainGage system was used to collect yield and moisture content data.

Statistical Analysis

Analysis of variance (ANOVA) was conducted using the GLIMMIX procedure in SAS 9.4 (SAS Institute Inc, 2018). Site-year was treated as a fixed effect, so that we could investigate site-year x treatment interactions and assess the effect of site-year conditions (e.g., soil test K concentration) on response to K fertilization. Block and crop within block were considered random effects. Letter groupings were assigned to least square means (P<0.05) using the Tukey-Kramer test. Where regression analysis was used, Proc Reg was used to conduct the F test (P<0.05).

Results and Discussion

Analysis of variance indicated K fertilization generally increased tissue K concentration in both barley and soybean, but that the magnitude of this difference depended on site-year (Table 4.3). The lack of interaction between fertilizer treatment and crop indicates that both barley and soybean were taking up some of the fertilizer K at midseason sample timing; that is, K fertilization resulted in an increase in tissue K concentration for both crops at Long Plain 2018 and Bagot 2018. These two site-years both had background STK concentrations below the current 100 mg kg^{-1} threshold for recommending an application K fertilization of barley and soybean. However, at Haywood 2018, where the background STK concentration was above the current threshold, the difference in tissue K concentration, for both barley and soybean, between K fertilized and unfertilized treatments was not significantly different. The tissue K concentration for each crop also depended on site-year, which is expected as a result of differences in soil K supply and dynamics of supply for different soils.

Table 4.3 Effect of K fertilization on tissue K concentration of barley and soybean, and differences in tissue K between K fertilized and unfertilized plots by site-year

	Site-Year[a]		
	Haywood 2018	Long Plain 2018	Bagot 2018
Crop		g kg^{-1}	
Barley	13.3*b*	12.1*b*	12.6*b*
Soybean	19.6*a*	23.0*a*	22.9*a*
Fertilizer			
K fertilized	16.9*a*	19.5*a*	19.5*a*
Control	16.0*a*	15.6*b*	16.0*b*
ANOVA	df	*Pr>F*	
Fertilizer	1	<0.0001	
Crop	1	<0.0001	
Crop*fertilizer	1	0.2497	
Site-year	2	0.1436	
Site-year*fertilizer	2	0.0049	
Site-year*crop	2	0.008	
Site-year*crop*fertilizer	2	0.3486	
Coeff Var (C.V.)		30	

[a]Means within columns for each crop or fertilizer treatment that are followed by the same letter are not significantly different (P<0.05)

Despite both Long Plain 2018 and Bagot 2018 having significant increases in K concentration of both barley and soybean tissue midseason, seed yield differences for the two crop species were not the same. Although K fertilization increased the yield of both crops, overall, there was an interaction between crop and fertilizer treatment. Barley seed yield was significantly increased with K fertilization, but soybean seed yield did not differ between K fertilized and unfertilized treatments (Table 4.4). The difference in effect of K fertilization on seed yield for the two crop types was consistent across both site-years, indicated by the lack of a significant site-year x crop x fertilizer interaction in the analysis of variance. The lack of soybean seed yield response to K fertilization was consistent with a lack of seed yield response in the 2017 and 2018 soybean small plot study. The difference in responsiveness to K fertilization between the two crops is similar to the difference Soper (1965) observed for rapeseed and barley grown at the same sites in his trials.

Table 4.4 Effect of crop on seed yield response to K fertilization and effect of site-year on barley and soybean seed yield response

	Fertilizer[a]		
Crop	K Fertilized	Control	
	——— kg ha^{-1} ———		
Barley	3610*a*	2971*b*	
Soybean	1620*a*	1701*a*	
		Site-Year[b]	
Crop	Haywood 2018	Long Plain 2018	Bagot 2018
	——— kg ha^{-1} ———		
Barley	1506*A*	3045*A*	5317*A*
Soybean	1210*A*	1869*B*	1896*B*
ANOVA	df	*Pr>F*	
Fertilizer	1	0.0449	
Crop	1	<0.0001	
Crop*fertilizer	1	0.0124	
Site-year	2	0.0131	
Site-year*fertilizer	2	0.0983	
Site-year*crop	2	0.0007	
Site-year*crop*fertilizer	2	0.2062	
Coeff Var (C.V.)		67	

[a]Means within rows followed by the same lower case letter are not significantly different
[b]Means within columns followed by the same upper case letter are not significantly different

In addition to a lack of seed yield response in the soybean small plot trials discussed in Chapter 2, there was no agronomically meaningful or statistically significant relationship between STK and relative yield for either crop (Figures 4.2, 4.3). However, the relationship was close to being significant for barley. That trend and the R^2 values suggest STK may be better suited to predicting yield response in barley than in soybean. Although there are a small number of data points in this study, this suggestion of the difference in predictive ability of STK between the two crops is supported by the difference in seed yield responsiveness discussed above. Nevertheless, similar to the other trials that we conducted, we were not able to use these data to predict where soybean is likely to respond to K fertilization, using the NH_4OAc test for exchangeable K.

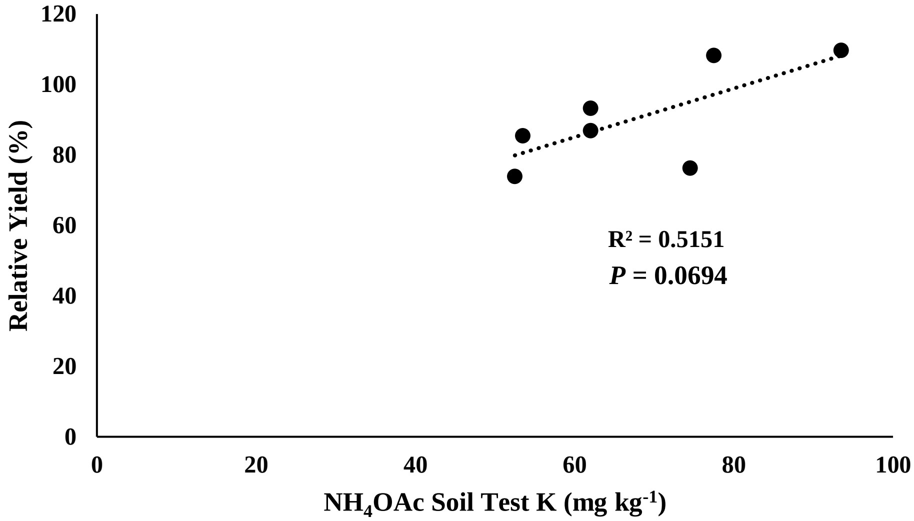

Figure 4.2 Relationship between concentration of NH_4OAc soil test K (STK) from 0-15 cm soil depth and barley relative yield for the control as a percent of fertilized for plots with <100 mg kg^{-1} NH_4OAc STK

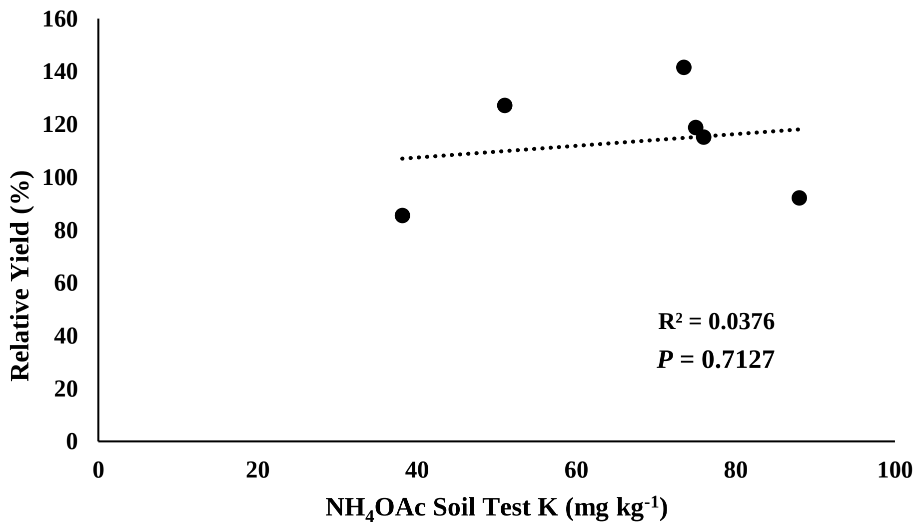

Figure 4.3 Relationship between concentration of NH_4OAc soil test K (STK) from 0-15 cm soil depth and soybean relative yield for the control as a percent of fertilized for plots with <100 mg kg^{-1} NH_4OAc STK

Conclusions

The significant seed yield increase in barley with K fertilization and the suggestion that STK may be a better predictor of barley yield response than soybean yield response, indicate differences in how K was accessed from the soil by the two crop types. While this study was not substantial enough to determine whether this is always the case, it highlights the need for further exploration into the dynamics of soybean access and extraction of soil K over the growing season. If soybean can access more soil K from the nonexchangeable pool than other crops can, traditional soil test K methods would not be expected to reliably predict where soybean yield response would occur, since those are based on exchangeable K alone. Understanding the mechanisms of soybean K access and uptake could help focus efforts for developing a more reliable soil test to reliably predict soybean yield response to K fertilization.

References

Grant, A., and Bailey, L.D. 1993. Fertility management in canola production. Can. J. Plant Sci. **73**: 651-670.

Pratt, P.F. 1965. Potassium. Pages 1022–1030 *in* Methods of Soil Analysis. Amer. Soc. Agron., Madison, WI.

SAS Institute. 2018. The SAS system for Windows. Release 9.4. SAS Inst., Cary, NC.

Soper, R.J. 1965. Effect of fertilizers on rape grown on stubble land. Proc. Manitoba Soil Science Society Annual Meeting, Winnipeg, MB.

Soper, R.J. 1971. Soil tests as a means of predicting response of rape to added N, P and K. Agron. J. **65**: 564-566.