Soybean is relatively nonresponsive to K fertilizer rate or placement in Manitoba soils

Authors: Bourns, Megan A., and Flaten, Don N.

Source: Canadian Journal of Plant Science, 102(4) : 835-847

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjps-2021-0254

Canadian Journal of
Plant Science

Article

Soybean is relatively nonresponsive to K fertilizer rate or placement in Manitoba soils

Megan A. Bourns and Don N. Flaten

Department of Soil Science, University of Manitoba, Winnipeg R3T 2N2, MB, Canada

Corresponding author: **Don N. Flaten** (email: Don.Flaten@UManitoba.ca)

Abstract

There has been little comprehensive potassium (K) fertility research for soybeans in Manitoba despite recent, rapid, expansion of soybean production in the province. Our main objective was to assess the efficacy of K fertilizer rate and placement combinations to increase K uptake and seed yield of soybeans grown on low K soils. Even though the seven sites had low concentrations of ammonium acetate-extractable soil test K (STK), midseason tissue K concentration increases with K fertilization, and, at several sites, visual deficiency symptoms in or near control plots, soybean seed yield did not respond to K fertilization, regardless of K fertilizer placement and rate. In a complementary field trial, barley, a crop known historically to respond well to K fertilization in Manitoba, had substantial (>20%) increases in yield with K fertilization where soybean did not respond. Ammonium acetate STK and the current 100 mg kg^{-1} threshold for recommending K fertilization for soybean and barley predicted barley yield response to K fertilization in our study, but did not predict soybean yield response.

Key words: soybean, potassium fertilization, ammonium acetate soil test, soil testing

Résumé

Malgré la rapide expansion du soja observée récemment au Manitoba, on s'est relativement peu intéressé à la fertilisation de cette culture avec des engrais potassiques (K), dans la province. Les auteurs voulaient évaluer l'efficacité du taux d'application et de la méthode d'épandage combinés sur l'absorption de l'oligoélément et le rendement grainier sur les sols carencés en K servant à la culture de la légumineuse. Même si les sept sites examinés se caractérisaient par une faible teneur en K extractible à l'acétate d'ammonium (NH4OAc), la concentration de l'oligoélément relevée dans les tissus à la mi-saison augmente avec l'usage de l'engrais. Toutefois, à plusieurs endroits où des signes visuels de carence ont été notés dans les parcelles témoins ou à proximité, le rendement grainier n'a pas réagi à l'addition d'un engrais potassique, peu importe le taux d'application et la technique d'épandage. Lors d'un essai sur le terrain complémentaire, le rendement de l'orge, culture qui a toujours bien réagi aux engrais K au Manitoba, a augmenté de façon appréciable (>20 %) après application de l'engrais potassique, contrairement au soja. Le dosage du K dans le sol avec l'acétate d'ammonium et le seuil de 100 mg de K par kilo actuellement recommandé pour le soja et l'orge ont permis de prévoir la réaction du rendement de la céréale à l'engrais dans le cadre de l'étude, mais il a été impossible d'en faire autant pour le rendement grainier du soja. [Traduit par la Rédaction]

Mots-clés : soja, engrais potassique, dosage avec l'acétate d'ammonium, analyse du sol

Introduction

Soybean (*Glycine max* (L.) Merr) demand for potassium (K) throughout the growing season is large compared with that of other crops and nutrients. Soybeans in Manitoba accumulate K_2O at a rate of approximately 4.5 kg ha^{-1} day^{-1}, with peak total accumulations over 220 kg K_2O ha^{-1} at the R6 growth stage (Heard 2005). Unlike other nutrients such as nitrogen and phosphorus which are integral to plant structural components, K is required mostly for physiological processes including enzymatic activation for photosynthesis, transport of water and nutrients, and regulating water intake through stomatal control (International Plant Nutrition Institute (IPNI) 1998). Soybean yield responses on soils with low plant available K result from an increase in pods per plant and seeds per pod with adequate K fertilization (Pettigrew 2008; Fernández et al. 2009). Potassium fertilization can also influence seed oil and protein content (Usherwood 1985) but these responses are inconsistent (Haq and Mallarino 2005; Farmaha et al. 2012; Krueger et al. 2013).

In addition to its large in-season requirement for K, soybeans remove more K in the grain at harvest (18–23 g K_2O kg^{-1} or 1.1–1.4 lb K_2O bu^{-1}) (Manitoba Agriculture 2007; Kaiser 2017) than most other field crops grown in Manitoba. In recent years, soybean has become a prominent crop in Manitoba rotations and this increased production (Statistics Canada 2018) coupled with soybean's high rate of K_2O

removal has increased total annual K_2O removal in Manitoba (Statistics Canada 2018). Additionally, the incidence of soybean K deficiency symptoms has increased, particularly in coarse-textured soils where soybean production is relatively new and ammonium acetate (NH_4OAc)-extractable soil test K (STK) is relatively low.

Current recommendations for soybean K fertilization in Manitoba are based on an NH_4OAc-extractable STK threshold of 100 mg kg^{-1} and include broadcast and incorporated applications of K_2O at rates of either 33 or 66 kg ha^{-1}, depending on STK (Manitoba Agriculture 2007). These thresholds and recommended rates for soybean are identical to those for wheat, barley, and other small grains, which remove less K in the grain at harvest compared with soybean and which have been more extensively researched in the Canadian Prairies. For example, previous research in Manitoba with barley indicated that K fertilization increased early season K uptake and this uptake was correlated with seed yield (Ewanek 1970). In Alberta, barley seed yield response to K fertilization increased in frequency and magnitude as STK decreased, especially if NH_4OAc-extractable STK exceeded 75–100 mg kg^{-1} (Malhi et al. 1993). However, the historical basis for K recommendations in soybean in the Prairies is limited to a single soybean K fertility study conducted at two site-years in Manitoba more than 30 years ago. The study included two rates of sidebanded K (50 or 100 kg K_2O ha^{-1}) and utilized one site classified as low in background K and one site high in background K. Seed yield did not increase in response to K fertilization at either site-year (Walley and Soper 1985). In addition to a small historical basis for the current recommendations, more recent recommendations from neighboring soybean-producing regions such as Ontario, North Dakota, and Minnesota include higher STK thresholds and K fertilizer rates (Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) 2017; Franzen 2018; Kaiser 2018).

As already mentioned, current recommendations in Manitoba are for broadcast and incorporated placement of K for soybean. However, band placement may provide better fertilizer-K access and plant uptake. Banding creates a nutrient-dense zone, which limits soil retention of K (Nkebiwe et al. 2016) and may facilitate increased root proliferation around the band, improving plant acquisition of this diffusion-mediated nutrient (Bell et al. 2009). Historically, in Manitoba, banding has been superior to broadcasting for K uptake, early-season dry matter yield, seed yield, and K use efficiency of wheat (Murage 1984). Additionally, Ewanek (1970) found the potential for barley seed yield to increase with banded K fertilizer compared with broadcast placement. More recently, a soybean study in Iowa found increased K uptake with banding compared with broadcast placement, but seed yield response was small and infrequent (Borges and Mallarino 2003)). The relatively high initial STK concentrations in that study could explain the infrequent seed yield response to banding, highlighting the importance of selecting K-deficient sites to examine the efficacy of K fertilization strategies.

In Manitoba, the NH_4OAc extraction for exchangeable and solution K is the recommended soil test to determine soil K fertility status. Traditionally, this extraction is done on an air-dried and ground soil sample, but in recent years NH_4OAc extraction from a moist soil has been investigated as an alternative method. In some cases, the moist soil extraction is more strongly related to crop seed yield response compared with the traditional dry soil extraction (Barbagelata and Mallarino 2012), but other studies indicate the dry soil extraction is still best correlated with seed yield (Breker et al. 2019). The effect of changing soil sample handling on soil K concentration is expected to be region-specific, as the effect of drying on soil K fertility status depends on the initial soil exchangeable K concentration, cation exchange capacity, mineralogy, and soil organic matter (Rakkar et al. 2016).

Ion exchange resins, such as Western Ag Innovations' Plant Root Simulator (PRS®) probes, quantify the soil K supply rate by diffusion in moist soil. This dynamic measure of nutrient supply is complementary to aqueous extraction methods to determine soil K fertility status, and may be particularly informative for nutrients such as K which move to plant roots via diffusion. The K supply rate measured by the PRS® probes depends on soil moisture and temperature, as well as biotic and abiotic competition (Qian and Schoenau 2002), the same conditions and factors that influence K supply to plant roots. Combining the quantity of NH_4OAc exchangeable K and PRS® K supply rates could inform differences in crop K nutrition status between site-years, and resulting tissue and seed yield responsiveness to K fertilization.

Midseason tissue K concentrations are a valuable tool to assess the efficacy of a K fertilization strategy. For soybean, uppermost mature trifoliate (UMT) leaves at growth stage R2–R3 are typically used to assess in-season K nutrition status (Clover and Mallarino 2013; Parvej et al. 2016*a*; Stammer and Mallarino 2018); however, alternative tissue tests using whole plant samples or stem samples are also an option (Fernández et al. 2009; Clover and Mallarino 2013; Bourns 2020). UMT leaf tissue K concentration is frequently responsive to K fertilization and an increase in tissue K concentration may be a prerequisite to yield response in some cases (Clover and Mallarino 2013); however, UMT K concentration increases have occurred even when there is no associated increase in seed yield (Fernández et al. 2009). Stammer and Mallarino (2018) determined the critical concentration range to be 15.6–19.9 g K kg^{-1} for soybean UMT tissue at the R2–R3 growth stage.

Although soybean tissue responses to K fertilization are more common than seed yield responses, increases in soybean seed yield with K fertilization, particularly on soils testing low in exchangeable K, have been documented (Clover and Mallarino 2013). Additionally, soybean seed yield has been statistically lower on low K fertility soils compared with medium and high K fertility soils (Fernández et al. 2009).

Similar to the use of midseason tissue K concentration, seed K concentration can be used as a postseason diagnostic tool to indicate K nutrition status and adequacy of the K fertilization strategy, using the critical range of 14.6–16.2 g K kg^{-1} (Parvej et al. 2016*b*).

Given the outdated K fertilizer recommendations for soybeans in Manitoba and prominence of soybean in Manitoba

 Can. J. Plant Sci. **102:** 835–847 (2022) | dx.doi.org/10.1139/CJPS-2021-0254

Table 1. Soil characteristics for each site-year.[a]

Site-year	Soil series	Soil classification	Surface soil texture
Elm Creek 2017	Kronstal	Gleyed Black Chernozem	Sandy loam
Haywood 2017	Almasippi	Gleyed Rego Black Chernozem	Sandy lacustrine
St. Claude 2017	Almasippi	Gleyed Rego Black Chernozem	Sandy lacustrine
Portage la Prairie 2017	Long Plain	Gleyed Regosol	Sandy lacustrine
Haywood 2018	Long Plain	Gleyed Regosol	Sandy lacustrine
Long Plain 2018	Neuenberg	Gleyed Rego Black Chernozem	Loamy lacustrine
Bagot 2018	Manitou	Orthic Black Chernozem	Loamy till

[a]Soil series, classification, and texture information are from detailed soil survey data, from AgriMaps (https://agrimaps.gov.mb.ca/agrimaps/).

crop rotations, the main objective of this research was to investigate the efficacy of K fertilizer rate and placement combinations for increasing soybean K uptake and seed yield on low K soils, where soybean K deficiency is most likely to occur. In addition, a surprising lack of seed yield response to K fertilizer treatments in 2017, regardless of STK status and fertilization practices, led to development of a supplemental study for the 2018 growing season. The objective for this supplemental study was to determine whether soybean is less sensitive to low STK and less responsive to K fertilization, compared with barley, a crop with an established history of response to K fertilization in soils with low STK in the Prairies.

Materials and methods

K fertilizer rate and placement study for soybean

Site establishment

Over the 2017 and 2018 growing seasons, a total of seven field site-years were established to investigate soybean response to K fertilization under dryland conditions in Manitoba (Haywood 17, Elm Creek 17, St. Claude 17, Portage la Prairie 17, Haywood 18, Long Plain 18, and Bagot 18) (Table 1). Sites were selected based on preliminary soil testing for NH_4OAc-extractable STK in the top 15 cm, analyzed from spring composite samples that were air-dried prior to analysis. Preference was given to sites with STK < 100 mg kg^{-1} and uniform topography. Preliminary soil tests at the sites selected for the study indicated that STK ranged from 49 to 117 mg kg^{-1}. A randomized complete block design with four replicates compared soybean response across six K fertilizer treatments: a control with no added K, two sidebanded treatments (33 or 66 kg K_2O ha^{-1}), and three broadcast and incorporated treatments (33, 66, or 132 kg K_2O ha^{-1}). The source of K fertilizer for all treatments was potassium chloride (potash, KCl, 0-0-60). Background fertility, including phosphorus and micronutrients, was applied as recommended from composite spring soil test results for each site. Broadcast and incorporated K treatments were hand spread and incorporated with two passes of a tandem disk before seeding. Sidebanded treatments were applied through the planter, at planting, 5 cm beside and 5 cm below the seedrow. In both years, sites were established between 17 and 19 May using a John Deere 1755 4-row precision planter (76 cm spacing between rows) and DKB005-52 soybean seed treated with Acceleron® (which contained Imidacloprid insecticide, plus Fluxapyroxad, Pyraclostrobin, and Metalaxyl fungicides) and Optimize® ST liquid inoculant. In addition, Cell-Tech™ liquid inoculant was applied through the planter, in the seedrow at a rate of 190 L ha^{-1}. Plots were 3 m × 8 m in length, with 8 m alleys between replicates, and an equal-sized buffer plot at each end of every replicate, for a total site area of 70 m × 28.4 m.

Soil measurements

Within a week of planting, ten 0–15 and 15–30 cm soil cores were collected from each control plot, composited by depth and analyzed for STK on a moist soil (MK) and a dry soil (DK) basis. Exchangeable plus solution NH_4OAc K were extracted using the Pratt (1965) method, using 1 mol/L NH_4OAc at a 1:5 soil to solution ratio; this method also includes solution K in the measurement of STK. An addendum to the method was added for MK, where the weight of the moist soil analyzed was increased by the moisture content of the respective sample to maintain a consistent soil mass of 5 g for both dry and moist samples. Extracts were analyzed with a Thermo Scientific iCAP spectrometer at Farmer's Edge Laboratories (Winnipeg, Manitoba). Even though the ammonium acetate method of extraction used in this study used the 1:5 soil:solution recommended by Pratt (1965) instead of the more common 1:10 ratio, a recent study in Quebec by Khiari et al. (2017) indicated very little influence of soil:solution ratios on the quantity of exchangeable K measured in mineral soils.

PRS® probes from Western Ag Innovations were used to measure K supply rates, in situ, at three times throughout the field season. Four pairs of probes (one anion and one cation) were buried approximately 10 cm deep in each control and 132 kg K_2O ha^{-1} treatment at each site-year, for a period of 2 weeks, to capture K supply at three times in the growing season: 2 weeks after planting to assess early season K supply, at soybean growth stage V4–V6 to investigate K supply during maximum vegetative growth and at R4–R5 to determine K supply during maximum soybean nutrient and water uptake. To insert the probes, a knife was used to cut a slot in the soil 10–15 cm away from a seedrow; a cation and anion probe pair were inserted in the slot, adjacent to one another. To ensure adequate probe–soil contact, a knife was used to make a back cut and soil around the probes was compressed with a boot heel.

Tissue measurements

At soybean growth stage R2–R3, 25 UMT samples were collected from each plot. Tissue samples were air-dried for at least 48 h, followed by oven drying at 60 °C in a forced air oven for 24 h. Samples were then ground using a Wiley Mill grinder and sent to AGVISE Laboratories (Northwood, ND) for K analysis by digestion with a nitric acid/hydrogen peroxide cook-down method, analyzed using inductively coupled plasma.

To investigate K uptake, whole above-ground plant sampling targeted growth stage V5–V6. However, at all site-years, growth stage V5–V6 coincided with R2, so whole plant samples were collected at the same time as UMT sampling. Ten whole plants per plot were cut at the soil surface, air-dried for at least 48 h, followed by oven drying at 60 °C in a forced air oven for 24 h. The oven-dry mass was collected before samples were ground using a Wiley Mill grinder, and sent to AGVISE Laboratories (Northwood, ND) for K analysis, using the same methodology as for the UMT samples. Uptake was calculated using the oven-dry mass and K concentration of the whole plant samples.

End of season measurements

The two center rows of each plot were harvested using a Wintersteiger Classic plot combine equipped with a HarvestMaster® Classic GrainGage to determine moisture and yield. Seed samples from each plot were analyzed for oil, protein, and K concentration. Oil and protein were determined using an NIR FOSS Infract 1241 Grain Analyzer. Seed K concentration was determined on dried and ground seed at AGVISE Laboratories (Northwood, ND) using the same process as for tissue K analysis.

Statistical analysis

The GLIMMIX procedure in SAS 9.4 (SAS Institute 2018) was used to conduct analysis of variance (ANOVA), in which site-year and treatment were fixed effects, while block (site-year) was a random effect. Treating site-year as a fixed effect allowed investigation of site-year by treatment interactions, to assess the influence of site-year specific characteristics (e.g., STK concentration) on soybean K response. Within the GLIMMIX procedure, unequal variances for sites that had missing data were corrected for using the Satterthwaite approximation. The Tukey–Kramer's test assigned letter groupings to least square means ($P < 0.05$). Ammonium acetate STK, oil, and protein content of the seed followed a log normal distribution, while PRS® K supply rates followed a gamma distribution. Respective data were transformed accordingly in the GLIMMIX procedure and back transformed to original units for reporting.

For regression analysis, Proc Reg determined the relationship and an F test threshold of $P < 0.05$ determined significance. Ammonium acetate STK data were transformed to log values prior to regression analysis.

Barley–soybean K response comparison study

Site establishment

Three trials comparing K fertilizer responses for soybean and barley were established in 2018, located in the same fields as the 2018 K rate/placement sites, discussed above. Ammonium acetate-exchangeable K was measured on air-dried and ground soil samples using procedures similar to the K rate/placement study.

Sites were established as a randomized complete block with a split-plot treatment design, where the main plot was crop (barley or soybean) and the subplot was fertilizer treatment (0 or 132 kg K_2O ha^{-1} broadcast and incorporated). Potassium fertilization treatments were broadcast by hand and incorporated with two passes of a tandem disk tillage operation prior to planting. Soybean plots were established using the same seed, treatment, and equipment as the K rate/placement study. Barley plots were planted with an Allis Chalmers double-disk press drill at a row spacing of 17.8 cm, using the variety Conlon, treated with Raxil Pro, a fungicide and insecticide seed treatment. Total site area was 70 m × 28.4 m, with 6.4 m × 8 m barley main plots and 6 m × 8 m soybean main plots.

Tissue measurements

Tissue samples were collected at the R2 stage of soybean, which corresponded approximately with barley anthesis, to determine if the effect of K fertilization on tissue K concentration was influenced by crop type. Twenty-five UMT leaves were collected from each soybean plot, and 80 uppermost leaves were collected from each barley plot. Samples air- and oven-dried, ground using a Wiley Mill grinder, and analyzed for K analysis by digestion with nitric acid/hydrogen peroxide cook-down method at AGVISE Laboratories (Northwood, ND). Potassium content in the digests was determined using ICP.

Harvest measurements

At maturity, a 3 m × 4 row area was hand harvested from the center of each barley plot. Samples were kept in mesh bags at room temperature for approximately 1 week, then processed through a Wintersteiger Classic plot combine to obtain yield and moisture content data using the HarvestMaster® Classic GrainGage system. At soybean maturity, 2 rows × 8 m from each soybean plot were harvested using the same Wintersteiger plot combine, again using the HarvestMaster® Classic GrainGage system to determine moisture and yield.

Table 2. Effect of site-year, sample depth, and soil sample drying on ammonium acetate exchangeable STK at planting for site-years in the K rate/placement study.

Soil sample preparation	Sample depth	Elm Creek 2017	Haywood 2017	St. Claude 2017	Site-year Portage la Prairie 2017	Haywood 2018	Long Plain 2018	Bagot 2018	Mean
	cm				STK[a] mg kg^{-1}				
Field-moist	0–15	100	37	56	70	98	117	53	
	15–30	116	92	142	80	70	72	35	
	Mean	107	58	88	74	82	91	43	74A
Air-dry	0–15	64	47	58	44	108	100	46	
	15–30	79	53	100	40	68	69	37	
	Mean	70	49	75	42	85	82	41	60B
Overall site-year	Mean	86a	53ab	81ab	55ab	83ab	86a	41b	
Depth mean	0–15	80A	42B	57B	55A	101A	106A	49A	
	15–30	96A	69A	118A	56A	68B	69B	36A	
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 lowercase letter within a row are not significantly different ($P < 0.05$); means followed by the same uppercase letter within a column are not significantly different ($P < 0.05$).

Statistical analysis

The GLIMMIX procedure in SAS 9.4 (SAS Institute 2018) was used to conduct ANOVA in a manner similar to the K rate/placement study. The Tukey–Kramer's test assigned letter groupings to least squared means ($P < 0.05$).

Results and discussion

K rate/placement study

STK and K supply rates

Ammonium acetate STK at planting was highly variable within individual site-years, regardless of whether the samples were analyzed on a moist or dry basis (Table 2). Regression analysis indicated a significant relationship between natural log values for DK and MK concentrations at both 0–15 cm ($P < 0.0001$) and 15–30 cm ($P < 0.0001$) depths (Figs. S1 and S2), but the slope and intercept for the relationship varied substantially between the two depths. Overall, MK was significantly greater than DK, which contrasts with other results in the literature. Barbagelata and Mallarino (2012) found DK to be 1.92 times greater than MK. Similarly, Breker (2017) found DK to be 1.27 times greater than MK. This difference cannot be attributed to methodology as similar sample preparation and analytical methods were used in all three studies. However, there could be mineralogical differences that affect the fate of K as an outcome of soil drying; perhaps mineral dehydration and interlayer collapse are the dominant processes for the Manitoba soils used in this study, whereas with the Barbagelata and Mallarino (2012) and Breker (2017) studies, more scrolling of mineral layers and subsequent K release could be the dominant process as a result of drying, especially in 2:1 layered silicates. The large spatial variability of K, the different outcomes between MK and DK for different regions, and the change in relationship between the two analysis methods with depth, exemplify the highly site-specific nature of K concentration and dynamics.

Similarly, PRS® K supply rates varied substantially within site-years and treatments. Potassium supply rates in the control at Haywood 2017, St. Claude 2017, and Bagot 2018 were an order of magnitude lower than for the four other site-years (Table 3). Despite this large variability, PRS® K supply rates were significantly greater in the 132 kg K_2O ha^{-1} treatment compared with the control for all site-years except Haywood 2018, and this treatment effect was consistent across burial periods. The increased K supply rate detected by the probes in the fertilized treatment indicates that a significant portion of the K fertilizer was available for plant uptake at most site-years. Potassium fertilization generally increased K supply rate, but the magnitude of difference between K supply of

Table 3. Effect of burial period and K fertilizer treatment on PRS® K supply rates for each site-year in the K rate/placement study.

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

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 period	12	0.0003*
Site-year × Treatment	6	0.0083*
Site-year × Burial × Treatment	12	0.8237
Coeff Var (C.V.)		87

*Significant at $P < 0.05$.
[a]Each burial period was 2 weeks in duration. Burial period 1 was 2 weeks after planting, burial period 2 was during the V4–V6 growth stage, and burial period 3 was during the R4–R5 stage.
[b]Within each column for burial period or K treatment, means followed by the same letter are not significantly different ($P < 0.05$).
[c]BI indicates broadcast and incorporated treatment.

fertilized and unfertilized treatments varied substantially between site-years. The differences in magnitude between fertilized and control plots, as well as the differences in K supply rates between control plots among site-years, exemplify the site-specific nature of K fertility. These differences are likely due to differences in soil type and characteristics, soil temperature, and available soil moisture; factors that govern K availability to plant roots, but also K diffusion to the probes (Qian and Schoenau 2002).

Tissue potassium concentration and uptake

ANOVA indicated a significant treatment effect and significant treatment–site-year interaction for UMT K concentration, indicating treatments were not having the same effect on soybean tissue K concentration across site-years (Table 4). For five of seven site-years, K fertilization did not significantly affect UMT K concentration. For the two site-years where potassium fertilization significantly increased UMT K concentration (Portage la Prairie 2017 and Bagot 2018), the highest rate at each placement resulted in significantly higher K concentration compared with the control. However, for both of these site-years, there were no significant differences in UMT K concentrations among the treatments which received K fertilizer.

In Iowa studies, Stammer and Mallarino (2018) established a critical range of 15.6–19.9 g K kg^{-1} for UMT K concentration at the soybean growth stage R2–R3. Using this critical range to determine soybean K nutrition status at our site-years, the control treatment exceeded this range at three of the seven site-years (Table 4). Therefore, according to tissue K thresholds for growing soybean in the US Midwest, four of the seven site-years had the potential for K deficiency. In addition, K fertilizer treatments were not always effective for increasing UMT K concentration above the critical range at the two site-years where K fertilization increased UMT K concentrations. At Bagot 2018, UMT K concentrations in all of the fertilized treatments exceeded the critical range determined for soybeans in Iowa. However, at Portage la Prairie 2017, only the 132 kg K_2O ha^{-1} treatment increased the UMT K concentration above the critical range.

Midseason dry-matter yield was unaffected by K fertilization (Bourns 2020); however, K uptake significantly increased with 66 kg K_2O ha^{-1} sidebanded, compared with the control, and this effect was consistent across site-years (Table 5). All other K fertilization treatments resulted in uptake similar to the control.

Prior to tissue sampling, starting as early as soybean growth stage V2–V3, visual symptoms of K deficiency were observed at several site-years in unfertilized borders and control plots. Soybean plants appeared to grow out of the deficiency symptoms until soybean growth stage R5, when symptoms developed in the upper canopy. Visual symptoms of K deficiency, in addition to suboptimal UMT K concentrations at the majority of site-years, indicate we were successful at identifying low K soils for our study, where yield response to K fertilization seemed likely and differences in performance of K fertilizer rate and placement combinations were expected.

Table 4. Effect of K fertilization on soybean's UMT leaf K concentration at V5–V6 (which coincided with R2) for each site-year for the K rate/placement study.

	Site-year[b]						
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot
Treatment[a]	2017	2017	2017	2017	2018	2018	2018
	g kg^{-1}						
0 kg K_2O ha^{-1}	20.8a	15.3a	20.3a	14.8b	18.8a	21.5a	17.0b
33 kg K_2O ha^{-1} SB	19.5a	16.0a	18.8a	18.0ba	19.3a	21.5a	20.3ba
66 kg K_2O ha^{-1} SB	19.8a	16.3a	20.3a	19.5a	19.8a	22.8a	24.3a
33 kg K_2O ha^{-1} BI	21.0a	15.8a	19.8a	19.3a	20.3a	20.5a	20.5ba
66 kg K_2O ha^{-1} BI	21.3a	16.8a	19.8a	19.8ba	19.3a	20.8a	23.0a
132 kg K_2O ha^{-1} BI	20.5a	17.8a	19.8a	21.8a	18.8a	23.8a	23.0a
ANOVA		df			Pr > F		
Treatment		5			0.0002*		
Site-year		6			0.0002*		
Site-year × treatment		30			0.0283*		
Coeff Var (C.V.)					15		

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

Table 5. Effect of K fertilization on soybean K uptake in whole above-ground plant material at V5–V6 (which coincided with R2) for each site-year.

	Site-year[b]							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot	All sites
Treatment[a]	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	13.2b
33 kg K_2O ha^{-1} SB	17.4	8.8	12.1	14.0	13.1	21.3	19.0	15.1ab
66 kg K_2O ha^{-1} SB	17.8	9.0	11.7	14.8	12.8	20.3	21.2	15.4a
33 kg K_2O ha^{-1} BI	17.7	8.3	9.7	15.1	12.9	18.1	15.6	13.9ab
66 kg K_2O ha^{-1} BI	17.7	10.4	11.7	16.5	10.0	17.8	18.2	14.6ab
132 kg K_2O ha^{-1} BI	17.0	8.7	11.4	17.0	12.0	19.6	19.9	15.1ab
ANOVA		df			Pr > F			
Treatment		5			0.0134*			
Site-year		6			<0.0001*			
Site-year × Treatment		30			0.3958			
Coeff Var (C.V.)					33			

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

Seed yield

Despite low background STK, the high K-consuming nature of soybeans and the presence of visual K deficiency symptoms in control plots at multiple site-years, there was no significant seed yield response to any K fertilization treatment for any site-year (Table 6). Additionally, there was no statistically significant or agronomically meaningful relationship between seed yield and NH_4OAc STK for moist or dried soil samples for either placement method (Figs. 1a and 1b).

The poor relationship between STK and relative yield for the critical range of STK values below 100 mg kg^{-1} was not improved by using STK values for moist instead of dry soil samples. Despite finding statistically significant differences in exchangeable K determined on moist versus dry soil samples, and the statistically significant relationship between MK and DK, the main reason for exploring the alternative methodology was to investigate whether MK was better than the traditional DK method for predicting soybean seed yield response to K fertilization. However, the smaller R^2 and P values for relationships between relative yield and MK compared with DK, indicate no benefit over the traditional dry extraction method.

The lack of a significant relationship between STK and relative yield for STK values <100 mg kg^{-1} also suggests that the 100 mg kg^{-1} STK threshold is too high for soybean in Mani-

Table 6. Effect of K fertilization on soybean seed yield at maturity for each site-year.

	Site-year[b]							
	Elm Creek	Haywood	St. Claude	Portage la Prairie	Haywood	Long Plain	Bagot	All sites
Treatment[a]	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	3422a	2769ab	2210b	2412b	936c	1415c	2297b	
ANOVA		df			$Pr > F$			
Treatment		5			0.4542			
Site-year		6			<0.0001*			
Site-year × Treatment		30			0.6861			
Coeff Var (C.V.)					39			

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

Fig. 1. (a) Relationship between concentration of NH_4OAc STK from 0 to 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 and R^2 values for the data points less than or equal to 100 mg kg^{-1} STK. (b) Relationship between concentration of NH_4OAc STK from 0 to 15 cm soil depth, determined on a moist soil, 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 and R^2 values for the data points less than or equal to 100 mg kg^{-1} STK.

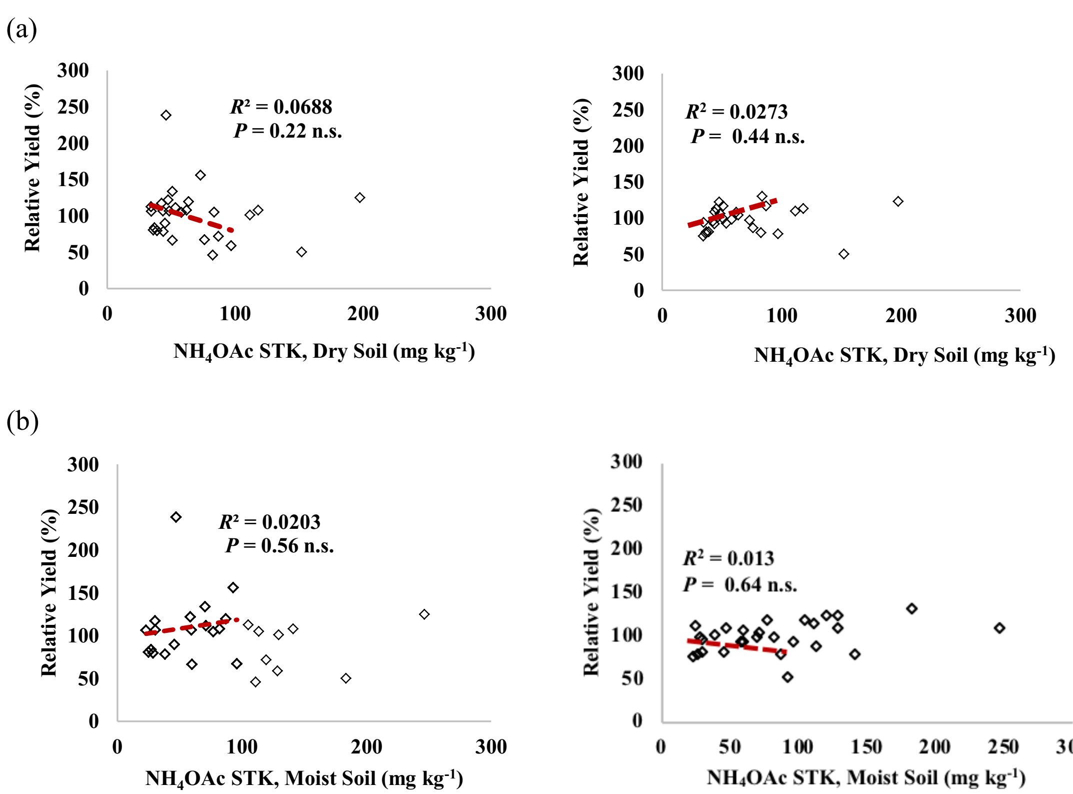

Table 7. Effect of K fertilization on soybean seed K concentration for each site-year.

Treatment[a]	Elm Creek 2017	Haywood 2017	St. Claude 2017	Portage la Prairie 2017	Haywood 2018	Long Plain 2018	Bagot 2018	All sites 2017–2018
	Site-year[b]							
	g kg^{-1}							
0 kg K_2O ha^{-1}	16.3	15.5	19.3	16.8	18.0	16.8	16.3	17.0b
33 kg K_2O ha^{-1} SB	16.8	17.5	19.8	16.8	18.8	17.0	16.8	17.6ab
66 kg K_2O ha^{-1} SB	17.5	17.8	19.5	19.3	19.5	17.8	16.3	18.2a
33 kg K_2O ha^{-1} BI	16.3	17.3	19.5	16.3	18.5	16.3	16.0	17.1b
66 kg K_2O ha^{-1} BI	17.3	16.5	19.8	18.5	18.8	18.0	17.3	18.0a
132 kg K_2O ha^{-1} BI	17.3	18.8	19.5	17.0	19.5	17.5	17.3	18.1a
ANOVA		df			$Pr > F$			
Treatment		5			<0.0001*			
Site-year		6			0.0006*			
Site-year × Treatment		30			0.2813			
Coeff Var (C.V.)					9			

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

toba and (or) the NH_4OAc test for exchangeable K was not a reliable predictor of K responsiveness for soybean at our site-years. Similar to these findings, researchers in North Dakota did not find any significant relationship between NH_4OAc STK, determined on a dry soil, and relative yield of corn in the first year of their study (Breker et al. 2019). In response to this unexpected finding, they investigated other methodologies including resin K and tetraphenyl boron extractable K, which measure some portion of the nonexchangeable K pool in addition to the solution and exchangeable pools. However, these tests did not improve their ability to predict corn yield response to K fertilization.

Seed K concentration

Potassium fertilization at rates of 66 or 132 kg K ha^{-1} increased seed K concentration compared with the control, and this effect was consistent across site-years (Table 7). This indicates that a portion of the K fertilizer was taken up by the soybean crop and the trend is similar to the trend in midseason UMT K concentration where rate seemed to have a greater effect on K concentration than placement.

Findings from 24 Canadian site-years of data suggested seed K concentration could be used as a postseason diagnostic tool to indicate the sufficiency of a K fertilization plan for soybean, using a critical range of 14.6–16.2 g kg^{-1} (Parvej et al. 2016*b*). According to this threshold, all treatments at all site-years except for the control at Haywood 2017, had sufficient K at maturity. This contrasts with midseason measurements, when UMT K concentrations in the control treatments indicated the threat of K deficiency at four of the seven site-years.

The change from midseason deficiency to end-of-season sufficiency in the indicators of K nutrition status is likely explained, at least in part, by the lack of sufficient growing season precipitation. Soybeans require more than 400 mm of precipitation to maximize yield potential (Licht et al. 2013); however, normal growing season precipitation for our site-years is less than 400 mm. Compounding the already limited moisture supply to achieve maximum yield potential, site-years received only 48%–69% of normal precipitation in 2017 and 2018, respectively. Suboptimal growing season precipitation resulted in a decline in yield potential as the season progressed, reducing soybean demand for K and shifting K nutrition status from deficient at R2 to sufficient by harvest.

The significant effect of K fertilization on UMT K concentration at some site-years suggests the potential for soybean K response if growing season precipitation was adequate, facilitating more late-season soybean growth and K demand. However, the small size of soybean plants in our study and suboptimal precipitation may be normal for Manitoba. Average soybean seed yield across our study was 2703 kg ha^{-1} in 2017 and 1549 kg ha^{-1} in 2018; these average yields are somewhat similar to the average soybean yield of 2370 kg ha^{-1} in Manitoba between 2015 and 2019 (Statistics Canada 2020). Given the average yield and likelihood of suboptimal moisture conditions based on long-term normal precipitation, soybean in Manitoba may not require as much K as in places with more late-season precipitation and greater seed yield potential.

Barley–soybean yield responsiveness comparison study

Tissue K concentration

In the supplemental study, K fertilization generally increased barley and soybean midseason tissue K concentrations (Table 8). The increases in tissue K concentrations as a result of fertilization were consistent for barley and soybean, as indicated by the lack of fertilizer–crop interaction, but the magnitude of increase varied among site-years. Fertilization significantly increased tissue K concentration in both crops

Table 8. Effect of K fertilization on midseason 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	13.3b	12.1b	12.6b
Soybean	19.6a	23.0a	22.9a
Fertilizer			
Control	16.0a	15.6b	16.0b
132 kg K_2O ha^{-1}	16.9a	19.5a	19.5a
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]Within each column for crop or fertilizer treatment, means that are followed by the same letter are not significantly different ($P < 0.05$).

compared with the control at Long Plain 2018 and Bagot 2018. However, at Haywood 2018 there was no significant difference in tissue K concentration with K fertilization compared with the control. This outcome was anticipated, because STK at Haywood 2018 exceeded Manitoba's 100 mg kg^{-1} threshold for recommending application of K fertilizer to soybean, barley, or most other field crops.

Seed yield

ANOVA indicated the main effect of K fertilization significantly influenced yield and that the interaction with crop was also significant (Table 9). That is, the effect of K fertilization on seed yield depended on crop species and this interaction was consistent across site-years. This interaction occurred because K fertilization increased barley seed yield by more than 20% compared with the control, but soybean yield was not significantly different between the two treatments.

The lack of soybean yield response to K fertilization in this study was consistent with the findings of the K rate/placement study. This type of difference between crop species in response to K fertilization has also been observed in other comparisons of crop responses to K fertilization in the Prairies. For example, Soper (1965) conducted a K study with rapeseed and barley in Manitoba and, similarly, found barley to respond to K fertilization where rapeseed did not, despite an anticipated yield response in both crops due to low concentrations of STK. Malhi et al. (1993) published similar results in a field study in Alberta where "rapeseed responded less often to K than barley and K placement was more critical for barley than for rapeseed".

Differences in root architecture between plant species, or even the same species in different environments, can affect K acquisition (White et al. 2013). Plant species, and genotypes within some species, including soybean, also differ in their access to nonexchangeable soil K from root release of organic compounds (Rengel and Damon 2008). Access to a portion of the nonexchangeable K pool could improve K uptake efficiency and reduce demand for fertilizer-K. Additionally, access to nonexchangeable K is not accounted for in the traditional NH_4OAc method for determining soil K fertility status and fertilizer recommendations. If soybeans can access the nonexchangeable K pool more readily than other crops, this could explain why NH_4OAc STK was unreliable for predicting soybean yield response to K fertilization in our study.

Overall discussion and conclusions

The lack of soybean yield response to any rate or placement of K fertilizer on soils testing low in K was surprising. Due to the lack of yield response, the ideal K fertilizer rate and placement combination could not be determined. We successfully selected sites classified as low in STK according to Manitoba's current guidelines for soybean. The selection of these sites appeared to be validated by visual K deficiency symptoms in or near the control plots, and UMT K concentrations below the critical range at most site-years. Despite the midseason indicators that yield response to K fertilization seemed likely, by harvest the soybean K nutrition status had shifted to sufficiency, indicated by the lack of yield increase as well as seed K concentrations that were above the critical range, even in control plots, for most site-years. These results were similar to those for a concurrent series of on-farm field-scale trials in Manitoba where soybean yield response to K fertilization was infrequent and not reliably predicted by NH_4OAc STK (Bourns 2020).

Table 9. Effect of crop on seed yield response to K fertilization and effect of site-year on barley and soybean seed yield response.

	Fertilizer[a]		
	Control	132 kg K_2O ha^{-1}	
Crop	kg ha^{-1}		
Barley	2971b	3610a	
Soybean	1701a	1620a	
	Site-year[b]		
Crop	Haywood 2018	Long Plain 2018	Bagot 2018
	kg ha^{-1}		
Barley	1506A	3045A	5317A
Soybean	1210A	1869B	1896B
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]Within rows, means followed by the same lowercase letter are not significantly different ($P < 0.05$).
[b]Within columns, means followed by the same uppercase letter are not significantly different ($P < 0.05$).

Suboptimal moisture conditions and spatial variability within site-years could have reduced the power of the NH_4OAc test to predict soybean yield response to K fertilization. As mentioned previously, soybeans require more than 400 mm of water to maximize yield potential (Licht et al. 2013); however, site-years for this study were located in regions where long-term average normal rainfall is less than 400 mm. Therefore, inadequate moisture as a yield-limiting factor for soybeans is a concern for these regions, even in years with normal growing season precipitation. Exacerbating the soybean crop's moisture deficit issue, the 2017 and 2018 growing seasons had only 48%–69% of normal growing season precipitation at our site-years. This lack of sufficient growing season moisture was certainly a yield limiting factor, especially on the coarse-textured soils that were the focus of our study, and could have reduced the ability of soybeans to respond to K fertilization. A decline in yield potential as the moisture deficit grew larger over the growing season could also explain the shift in soybean K nutrition status, from deficiency midseason to sufficiency at the end of the season, as demand for nutrients declined with decreasing yield potential. The significant increases in PRS® K supply rate, midseason tissue K concentration, K uptake, and seed K concentration in response to K fertilization, for most site-years, indicate that K fertilization increased the amount of bioavailable K in soil and uptake by plants. If environmental conditions had been more favorable to support higher yield potential, the increase in K uptake could have been a precursor to seed yield response to K fertilization.

In addition to the suboptimal moisture conditions, the large variability in STK within site-years could have masked any yield responses that may have occurred with more uniform background STK concentrations, and adequate moisture supply. Therefore, under different conditions, NH_4OAc STK may have been a more reliable predictor of yield response to K fertilization for our site-years.

Perhaps, though, NH_4OAc STK is not a reliable indicator of bioavailable K for soybean in Manitoba soils. The contribution of nonexchangeable K, not measured in the NH_4OAc test, to crop K nutrition has been documented in several studies elsewhere (Havlin and Westfall 1985; McLean and Watson 1985; Brar et al. 2016). Despite this knowledge, the challenge comes in quantifying the bioavailable K released over the length of the growing season and the findings of Breker et al. (2019) demonstrate the challenge in finding reliable methods for this purpose.

Plant cultivars and species also play a role in soybean K uptake and use (Rengel and Damon 2008). Thus, K response in our study may have been larger with the addition of another, more responsive, soybean variety. There may also be inherent differences between soybean and other crop species in K responsiveness and effectiveness of the NH_4OAc test, as Soper (1965) and Malhi et al. (1993) found with barley and rapeseed, and our supplemental study indicated for barley and soybean. Alternatively, the critical STK threshold for NH_4OAc STK may be lower for soybean than for other crop species. However, this seems unlikely as Manitoba's STK threshold for soybeans is already lower than that of neighboring soybean-producing regions with similar production systems and soil types. Ammonium acetate STK, with a critical threshold of 100 mg kg^{-1}, successfully predicted barley yield response to K fertilization, but this traditional STK method and (or) threshold does not appear to be suitable for predicting soybean yield response to K fertilization in coarse-textured soils of Manitoba.

Additional research is required to determine what soil test method and threshold best predicts soybean yield response to K fertilization, especially for growing season moisture conditions that are near or above normal for Manitoba. Furthermore, investigation into the mechanisms of soil K supply and plant K uptake 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 reliably predicted, investigation into the K fertilizer rate and placement combination best suited to increasing seed yield on coarse textured soils should be readdressed.

Acknowledgements

The authors acknowledge the technical assistance of Kris Davy, Jeremy Gladish, Lanny Gardiner, Trevor Fraser, and Manitoba Pulse and Soybean Growers staff, as well as the advice of Francis Zvomuya, Yvonne Lawley, Kristen Macmillan, and John Heard. In addition, this project could not have been conducted without the generous cooperation of the farmers who hosted the field sites.

Article information

History dates

Received: 18 November 2021
Accepted: 13 April 2022
Accepted manuscript online: 20 April 2022
Version of record online: 22 July 2022

Copyright

Author information

Author contributions

MAB – investigation and original draft. DNF – supervision, editing, and project administration.

Competing interests

The authors declared that no competing interests exist.

Funding information

This work was funded primarily by the Manitoba Pulse and Soybean Growers and Western Grains Research Foundation, with supplemental support from Nutrien, Dekalb, and Western Ag Innovations.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/CJPS-2021-0254.

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. doi:10.2136/sssaj2012.0253.

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. doi:10.2136/sssaj2003.1920.

Bourns, M. 2020. Soybean response to potassium fertility and fertilizer in Manitoba. M.Sc. thesis, University of Manitoba, Manitoba. p. 139.

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. doi:10.1080/15427528.2015.1106422.

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

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. doi:10.2136/sssaj2018.10.0376.

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. doi:10.2136/sssaj2012.0223.

Ewanek, J.N. 1970. The effect of potassium fertilization on cereal crops grown on calcareous Manitoba soils. M.Sc. thesis, University of Manitoba, Winnipeg, Manitoba. p. 112.

Farmaha, B.S., Fernández, F.G., 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. doi:10.2134/agronj2012.0010.

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. doi:10.1007/s11104-009-9900-9.

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

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. doi:10.2134/agronj2004.0215.

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. doi:10.2136/sssaj1985.03615995004900020019x.

Heard, J. 2005. Nutrient uptake and partitioning by soybeans in Manitoba [online]. Available from https://www.manitobapulse.ca/wp-content/uploads/2019/03/Heard-nutrient-uptake-and pratitioning.pdf [accessed14 October 2021].

International Plant Nutrition Institute (IPNI). 1998. Functions of potassium in plants [online]. Available from http://www.ipni.net/publication/bettercrops.nsf/0/64ED48A22E45ABD48525798000820367/$FILE/Better%20Crops%201998-3%20p04.pdf [accessed 5 December 2017].

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

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

Khiari, L., Gallichand, J., and Bouslama, S. 2017. Volume or weight soil sampling for extracting mehlich III elements with routine analyses?

Commun. Soil Sci. Plant Anal. **48**: 1753–1763. doi:10.1080/00103624.2017.1395445.

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. doi:10.2135/cropsci2012.06.0372.

Licht, M.A., Wright, D., and Lenssen, A.W. 2013. Soybean response to drought[online]. Available from https://lib.dr.iastate.edu/extension_ag_pubs/190 [accessed 29 June 2020].

Malhi, S.S., Nyborg, M., Penney, D.C., Kryzanowski, L., Robertson, J.A., and Walker, D.R. 1993. Yield response of barley and rapeseed to K fertilizer: influence of soil test k level and method of placement. Commun. Soil Sci. Plant Anal. **24**: 2271–2280. doi:10.1080/00103629309368954.

Manitoba Agriculture. 2007. Manitoba soil fertility guide [online]. Available from https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertilityguide/pubs/soil_fertility_guide.pdf [accessed 24 January 2019].

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

Murage, P.M. 1984. Potassium as a limiting nutrient for maximum production of wheat in Manitoba. M.Sc. thesis, University of Manitoba, Winnipeg, Manitoba. p. 179.

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. Field Crops Res. **196**: 389–401. doi:10.1016/j.fcr.2016.07.018.

Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). 2017. Agronomy guide for field crops[online]. Available from http://www.omafra.gov.on.ca/english/crops/pub811/pub811.pdf [accessed 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**: 1231–1243. doi:10.2136/sssaj2016.02.0030.

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. doi:10.2134/agronj2015.0353.

Pettigrew, W.T. 2008. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiol. Plant. **133**: 670–681. doi:10.1111/j.1399-3054.2008.01073.x.

Pratt, P.F. 1965. *In* Potassium. Methods of Soil Analysis. American Society of Agronomy, Madison, WI. pp. 1022–1030.

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. doi:10.4141/S00-091.

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. doi:10.1080/01904167.2016.1161790.

Rengel, Z., and Damon, P.M. 2008. Crops and genotypes differ in efficiency of potassium uptake and use. J. Physiol. Plant. **133**: 624–636. doi:10.1111/j.1399-3054.2008.01079.x.

SAS Institute 2018. The SAS system for Windows. Release 9.4 [computer program]. SAS Institute Inc., Cary, NC.

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

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. doi:10.2136/sssaj2017.06.0179.

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 from http://www5.statcan.gc.ca/cansim/a47 [accessed 12 January 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 from https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210035901 [accessed 26 June 2020].

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

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, Manitoba.

White, P.J., George, T.S., Gregory, P.J., Bengough, A.G., Hallett, P.D., and McKenzie, B.M. 2013. Matching roots to their environment. Ann. Bot. **112**: 207–222. doi:10.1093/aob/mct123. PMID: 23821619.