DIVISION S-4—SOIL FERTILITY & PLANT NUTRITION

Critical Leaf Potassium Concentrations for Yield and Seed Quality of Conservation-Till Soybean

Xinhua Yin and Tony J. Vyn*

ABSTRACT

Leaf K concentrations needed for optimum soybean [*Glycine max* (L.) Merr.] production under conservation tillage systems may be different from those in conventional tillage (moldboard plow) because soil properties (such as soil-test K distribution) and soybean root distribution within the soil profile under conservation tillage systems differ from those in conventional tillage. Little information is available about adequate leaf K concentrations for soybean on conservation-tilled soils with significant vertical soil-test K stratification. This study was conducted at three locations in Ontario, Canada from 1998 through 2000 to estimate the critical leaf K concentrations for conservation-till soybean on K-stratified soils with low to very high soil-test K levels and a 5- to 7-yr history of no-till management. Three K fertilizer placement methods (band placement, surface broadcast, and zero K), two conservation tillage systems (no-till and fall tandem disk), and two soybean row widths (19 and 38 cm) were used to create a wide spectrum of production environments. For maximum seed yield, the critical leaf K concentration at the initial flowering stage (R_1) of development was 24.3 g kg^{-1}. This concentration is greater than the traditional critical leaf K values for soybean that are being used in Ontario and in many U.S. Corn Belt states. Critical leaf K values for the maximum concentrations of K, oil, and isoflavone in seed were 23.3, 24.1, and 23.5 g kg^{-1}, respectively. The extent of vertical soil-test K stratification seems to be one of the factors contributing to apparently higher critical leaf K concentrations for conservation-till soybean.

Analysis of nutrient concentrations in plant tissue at certain critical growth stages has often been used as an effective tool to diagnose nutrient disorder problems in field crop production. By analyzing plant tissue, one can compare the nutrient concentrations with the recommended critical values (a single value or range of critical concentrations) to confirm nutrient deficiency when visual symptoms are present and to determine whether nutrient concentrations are adequate to produce maximum plant growth or seed yield (Plank, 1979). Another important value of plant analysis is the prevention of severe nutrient deficiency in plants (Ulrich and Hills, 1967), because plant analysis can be used to detect hidden hunger (i.e., invisible symptoms of growth disorder caused by nutrient deficiency). It may be possible to alleviate the hidden hunger and prevent further development into severe nutrient deficiencies (Tisdale et al., 1985). Many crop producers, therefore, rely on crop monitoring to prevent nutrient deficiencies from limiting potential crop yield.

Critical nutrient concentration is defined as the concentration of a specific nutrient within a specific plant part at which growth or yield begins to decline (Ulrich and Hills, 1967). According to this approach, a single concentration value is assigned to a point where the plant nutrient shifts from deficient to adequate. Because of variations in the soil, climate, and other production environments, a range of concentrations is also used to represent critical nutrient concentration. In Ontario, the critical trifoliate leaf K concentration was 12.0 g kg^{-1} for soybean at the initial flowering stage (Ontario Ministry of Agriculture, Food, and Rural Affairs, 1997). This value had not changed with the advent of conservation tillage practices and narrow-row soybean production. The K sufficiency range of 17.1 to 25.0 g kg^{-1} for the upper fully developed trifoliate leaves of soybean—sampled before pod set—proposed by Small and Ohlrogge (1973) in Ohio is still widely used in many Corn Belt states. Another adequate leaf K range for soybean at the initial flowering stage was estimated to be 17.5 to 25.0 g kg^{-1} by Plank (1979) in Georgia. For the end of flowering stage, an average critical leaf K concentration of 21.5 g kg^{-1} was reported by de Mooy and Pesek (1970) in Iowa. The critical leaf K value for soybean at the early pod stage was found to be approximately 20 g kg^{-1} in Florida (Sartain et al., 1979). All of the latter critical leaf K values were established for soybean production in conventional tillage and (predominantly) in wide row widths.

The use of conservation tillage for soybean production in North America has increased remarkably since the late 1980s. Currently, about 50% of soybean acreage is under some kind of conservation-till management in the USA. Production management shifts such as those from conventional tillage to conservation tillage and the use of narrow instead of wide rows, combined with overall yield improvements, have raised new concern about the applicability of critical leaf K concentrations originally designed for conventional-till soybean to conservation-till soybean production. This concern may be most acute on long-term no-till fields where significant vertical soil-test K stratification has occurred. There-

X. Yin, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011-1010. T.J. Vyn, Dep. of Agronomy, Purdue Univ., West Lafayette, IN 47907-2054. Research was supported by Purdue Research Foundation, Agricultural Adaptation Council of Canada, Ontario Soybean Growers' Marketing Board, and Ontario Ministry of Agriculture, Food, and Rural Affairs. Received 9 Jan. 2003. *Corresponding author (tvyn@purdue.edu).

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fore, there is a need to verify whether the historic critical leaf K concentrations can be applied to current conservation-till soybean production systems.

Long-term no-till management has resulted in significant vertical soil-test K stratification within the common soil-test sampling depth (0–15 or 0–20 cm) (Holanda et al., 1998; Howard et al., 1999; Karathanasis and Wells, 1989; Yin and Vyn, 1999). In contrast, soil-test K distribution within the plow layer is quite uniform in fields that are routinely moldboard plowed (Cruse et al., 1983; Fink and Wesley, 1974).

Although vertical soil-test K stratification with conservation-till management generally does not change the total available K in the top 15 or 20 cm of soil, it does result in stratification within this layer because of greater exchangeable K in the top 5 (or 10) cm compared with the next 5 to 10 cm. This stratification may increase plant K uptake in the early stages due to the enhanced soil-test K levels near the surface, but may reduce K uptake during later growth periods because of the lower soil-test K levels in the 10- to 20-cm layer. Furthermore, vertical soil-test K stratification may reduce plant K uptake, and thus increase the likelihood of plant tissue K deficiency and grain yield loss in droughty growing seasons, because soil K availability and root growth and activity near the surface are more vulnerable to drought stress than those at the 10- to 20-cm depth. In addition, the presence of crop residue at the soil surface in conservation tillage systems usually results in lower soil temperature because of higher soil moisture in the surface layer; these conditions also may reduce soil K availability through reducing root growth early in the season (Barber, 1971; Fortin, 1993). The risks of reduction in plant K uptake by drought or low temperature in conservation-till fields become severe when soil-test K concentration below 10 cm is too low to optimize plant K uptake.

In northern production regions, soybean seed yield generally increases as row width decreases (Ablett et al., 1991; Bullock et al., 1998; Ethredge et al., 1989). Because conservation-till soybean production in North America is predominantly in narrow row widths (<40 cm), and deep banding of K fertilizer is now a viable alternative to surface broadcasting in conservation-till soybean production, soybean yield relationships to mid-season leaf K nutrition status also may be affected by the proximity of soybean rows to fertilizer bands (Yin and Vyn, 2003).

Previous critical leaf K concentration research for soybean has focused on maximum yield with little regard to seed quality components. Potassium concentration in plants is very important to high-quality and value-added soybean production because K is widely involved in plant metabolism. Oil and isoflavone concentrations in soybean seed are among the most important seed quality components related to soybean-based foods. Potassium fertilization has been reported to significantly increase oil and isoflavone concentrations in soybean seed produced on low- to medium-test K soils (Gaydou and Arrivets, 1983; Vyn et al., 2002; Yin and Vyn, 2003). Because soybean seed yield is made up of a variety of different seed quality components, the critical leaf K concentration associated with a maximum seed quality component may be different from that for maximum seed yield or another seed quality component. Therefore, it is important for value-added soybean production to determine the critical leaf K concentrations for these key seed quality components and seed yield simultaneously.

The objectives of this study were to: (i) determine the critical trifoliate leaf K concentrations of soybean at the initial flowering stage for maximum seed yield and quality components in conservation-till production systems, and (ii) evaluate the influences of vertical soil-test K stratification on soybean critical leaf K concentrations.

MATERIALS AND METHODS

This study was conducted near Kirkton, Strathroy, and Paris, in Ontario, Canada from 1998 through 2000 to quantify the relationships of soybean seed yield and seed quality components with initial flowering stage (R_1) (Fehr et al., 1971) leaf K concentrations. Selected soil properties at each location are presented in Table 1. Three K fertilizer placement methods (band placement, surface broadcast, and zero K), two conservation tillage systems (no-till and fall tandem disk), and two soybean row widths (19 and 38 cm) were used to create a wide spectrum of soybean production environments. The fields used for this study had been under continuous no-till management for 5 to 12 yr before treatment initiation and all K fertilizer was broadcast on the soil surface during that period. The previous crop in all three seasons was winter wheat (*Triticum aestivum* L.) at both Kirkton and Paris locations and corn at

Table 1. Soil physical and chemical properties of the Ap horizon (0–15 cm) for the nine site-years.

Characteristic, unit	Kirkton			Strathroy			Paris		
	1998	1999	2000	1998	1999	2000	1998	1999	2000
Texture	silt loam	silt loam	silt loam	clay loam	silty clay loam	loam	silt loam	loam	sandy loam
Sand, g kg^{-1}	134	115	173	304	38	378	380	394	371
Silt, g kg^{-1}	696	707	602	483	581	413	539	489	531
Clay, g kg^{-1}	170	178	225	213	381	209	81	117	98
pH	7.0	6.8	7.7	7.4	6.8	7.3	6.6	6.4	6.0
Organic C, g kg^{-1}	34	29	36	37	37	37	23	20	20
Available P, mg kg^{-1}†	10	21	12	30	25	18	10	28	15
Available Mg, mg kg^{-1}‡	186	202	229	201	236	166	159	161	127
Available K, mg L^{-1}§	92	73	90	155	134	96	35	35	54

† Sodium bicarbonate extractable P (Schoenau and Karamanos, 1993).
‡ Ammonium acetate extractable Mg (Simard, 1993).
§ Ammonium acetate extractable K (Bates and Richards, 1993).

Table 2. Treatments for the experiments at Kirkton and Strathroy (1998–2000).

		K placement	
No.	Tillage	Method	Timing
1	no-till	15 cm deep via coulter	fall
2	no-till	7.5 cm deep 3 d before planting	spring
3	no-till	surface applied	fall
4	no-till	zero K	NA†
5	fall disk	7.5 cm deep 3 d before planting	spring
6	fall disk	surface applied before tillage	fall
7	fall disk	zero K	NA

† Not applicable.

Strathroy. At each location, the experiment was conducted for three consecutive years with the same design in either adjacent areas within the same field or in adjacent fields. Daily rainfall and air temperature were recorded during the entire growing season each year at all three locations.

Soil Classification

At Kirkton, the soil was classified as a medium, mixed, weakly to moderately calcareous Typic Hapludalf. At Strathroy, soil texture varied among site-years. In 1998, the soil was a fine and moderately fine, mixed, alkaline, moderately to very strongly calcareous Typic Humaquept; the soil in 1999 was a fine, clayey, mixed, alkaline, strongly calcareous Typic Hapludalf; the 2000 site was a fine, and moderately fine, mixed, moderately to very strongly calcareous Typic Hapludalf. The soil at Paris for all three seasons was classified as a medium, mixed, alkaline, moderately to very strongly calcareous Typic Hapludalf.

Experimental Design and Implementation

A randomized complete block design with four replicates was used in each season at both Kirkton and Strathroy. There were seven treatments in total consisting of the incomplete combinations of conservation tillage systems and K application timing and methods (Table 2). Two conservation tillage systems of no-till and fall disk were used in this experiment. The fall tandem disk tillage was conducted to a depth of 10 cm. The four K placement methods utilized in this study were 15-cm deep banding in the fall (fall band), 7.5-cm deep banding in the spring (spring band), surface broadcasting in the fall (fall broadcast), and zero K. Potassium fertilizer was applied at a rate to supply 100 kg K ha^{-1} as muriate of potash (KCl). Soybean was planted in 38-cm rows in all the treatments at both locations. Each plot was 21 m long and 3 m wide.

At Paris, a randomized complete block split-plot design with four replicates was used. Potassium band placement methods were randomly assigned to the whole plots, and soybean row widths were assigned to the split-plots. Only spring-applied K was evaluated in this experiment. The four K placement methods were 76-cm band, 38-cm band, surface broadcast, and zero K. Potassium fertilizer was placed 10 cm deep in bands separated in width by 76 or 38 cm. Surface broadcasting involved uniform broadcasting to the soil surface. When K was applied, the rate was 100 kg K ha^{-1} as muriate of potash. Potassium fertilizer was applied within 3 d before soybean planting in each season. Soybean row widths were 38 and 19 cm for each K treatment. Each split-plot was 21 m long and 3 m wide.

Soybean was planted on 26 May 1998, 19 May 1999, and 30 May 2000 at Kirkton and on 23 May 1998, 4 June 1999, and 1 June 2000 at Strathroy. Soybean rows were positioned directly on top of the fertilizer bands in both tillage systems. The locations of K fertilizer bands were marked with small flags during K application for both tillage systems to locate these K fertilizer bands at soybean planting. Soybean 'OAC Bayfield' was used in 1998, and 'First Line 2801R' (First Line Seeds, Guelph, ON) was grown in 1999 and 2000 at Kirkton. Soybean 'NK S19-90' was planted in 1998 and 'NK S08-80' (Northrup King, Arva, ON) in 1999 and 2000 at Strathroy. The final soybean population for each treatment was greater than 240 000 plants ha^{-1} (data not presented). More details about crop management and soybean yield response to K application and placement in this experiment are available from a previous publication (Yin and Vyn, 2002).

At Paris, soybean 'OAC Bayfield' was no-till planted on 19 May 1998, 14 May 1999, and 26 May 2000. The final soybean population was higher than 310 000 plants ha^{-1} in both row widths. In the 76-cm band fertilizer treatment, either 50 or 25% of soybean rows were planted directly over K fertilizer bands in the 38- and 19-cm row widths, respectively. In the 38-cm band fertilizer treatment, either all or half of the soybean rows were planted over the K fertilizer bands for 38- and 19-cm row widths, respectively. More details about crop management and soybean yield response to K application and placement were published previously (Yin and Vyn, 2003).

Soil and Plant Sampling

Composite soil samples (10 cores per sample, 2.5 cm in diameter) were collected at four soil depth intervals (0–5, 5–10, 10–20, 20–30 cm) randomly from each plot (or split-plot) during the spring of each year before treatment initiation at all three locations.

A leaf sample consisting of 20 most recently fully developed trifoliate leaves including the petiole was taken from 20 plants at the initial flowering stage (R_1) in mid- to late-July of each year (27 July 1998, 16 July 1999, and 25 July 2000 at Kirkton; 27 July 1998, 23 July 1999, and 24 July 2000 at Strathroy; and 22 July 1998, 20 July 1999, and 20 July 2000 at Paris) from each plot (or split-plot) for the determination of midseason leaf K concentrations.

Soybean seed yield was determined by harvesting a 1.0-m width of soybean (three rows in 38-cm row width, and six rows in 19-cm row width) at the center of each plot for the entire plot length with a plot combine and adjusting to 130 g kg^{-1} moisture content. Seed samples were taken during harvest for the determination of seed K, oil, and isoflavone concentrations.

Soil Testing and Plant Analysis

After soil samples were air dried, ground to pass through a 2-mm sieve, and thoroughly mixed, 1.0 mL of soil measured with a 1-mL scoop was placed into a 50-mL flask, and 10 mL of 1 *M* ammonium acetate (NH_4OAc) buffered at pH of 7.0 was added; the resulting solution was shaken for 15 min and filtered (Bates and Richards, 1993). Potassium in the filtrates was determined by atomic absorption spectroscopy. Soil-test K concentration for the 0- to 15-cm depth interval used to report general soil characteristics (Table 1) was calculated as the average of soil K concentrations at the 0- to 5-, 5- to 10-, and 10- to 20-cm depth intervals with the assumption that soil-test K concentrations at the 10- to 15- and 10- to 20-cm depth intervals are equal. Boundaries of soil-test K concentrations at low, medium, high, very high, and excessive categories for soybean in Ontario are $<$61, 61 to 120, 121 to 150, 151 to 250, and $>$250 mg L^{-1} (milligrams of K per liter of soil), respectively (Ontario Ministry of Agriculture, Food, and Rural Affairs, 1997).

Leaf and seed samples were dried in a forced-air oven at 65°C for at least 3 d and then ground in a Wiley mill (Arthur K. Thomas Co., Philadelphia, PA) to pass through a 1-mm sieve. Leaf and seed samples were digested using a dry ash method (Miller, 1998); K dissolved in 0.1 *M* HCl solution was determined by atomic absorption spectroscopy. Seed oil concentration was determined using GrainSpec (Foss Electric, Great Britain), near infrared reflectance spectroscopy calibrated with a gravimetric method. Total isoflavone concentrations in seed were determined using a high-performance liquid chromatography method outlined by Vyn et al. (2002).

Statistical Analysis

Leaf K concentrations at the initial flowering stage in each season at both Kirkton and Strathroy were analyzed using an analysis of variance appropriate for a randomized complete block design. Orthogonal linear contrasts were conducted to compare means of treatments (or treatment combinations) by using the GLM procedure in the SAS package (SAS Institute, 2002). Leaf K concentrations at Paris were analyzed for each season using an analysis of variance appropriate for a randomized complete block split-plot design. Mean separations were accomplished using Fisher's protected LSD. Probability levels lower than 0.05 were designated as significant for all statistical analyses.

Based on the relationship of crop yield with leaf K concentration, a quadratic-plateau model is an appropriate model to describe the relationship between crop yield and leaf K concentration in a wide range of leaf K nutrition status ranging from severely deficient to luxurious uptake. Therefore, a quadratic-plateau model was used in this study to estimate the critical concentrations of midseason trifoliate leaf K for maximum seed yield and maximum concentrations of K, oil, and isoflavone in seed by using the Nonlinear (NLIN) procedure in the SAS package (SAS Institute, 2002). The critical leaf K value determined by a quadratic-plateau model is the leaf K concentration at which the two portions (quadratic and plateau) of the model join. In other words, when the quadratic-plateau model was fitted to leaf K concentration as a function of relative yield or a relevant quality component, the critical leaf K value was the minimum leaf K concentration at which the maximum predicted yield or quality component was produced.

To minimize the influences of year and location (due to soil types, weather conditions, cultivars, etc.), all data of soybean yield and quality components were normalized as follows: The highest numeric value of yield or a quality component among all treatments within each site-year was assumed to equal 100% yield or quality component for that site-year. The percentage values relative to this maximum value were calculated for the other treatments within that site-year. Values of yield and quality components were calculated within each site-year before pooling data across years and locations. Treatment means across the replicates within each site-year were used instead of individual plot data. Because midseason leaf K concentration was affected by both initial soil K fertility levels and K fertilizer added, and the treatments within each site-year in this study differed significantly in initial soil K levels and K fertilizer applications (application rate, timing, and placement methods), each treatment within each site-year was used as a data point to produce as many data points as possible for each variable.

Nonlinear regression of a quadratic-plateau model was conducted by using soybean seed yield or the concentration of K, oil, or isoflavone in seed as the dependent variable and leaf K concentration as the independent variable for the entire data set including all the treatments, years, and locations as well as for the data subset comprised of data from just the no-till treatments in all site-years.

Vertical stratification coefficient of soil-test K (KSC) is defined as the quotient of soil-test K concentration in the 0- to 5-cm layer divided by K level at the 10- to 20-cm depth. The KSC value for each treatment within a site-year was calculated by using the averages of soil-test K concentrations over the four replicates (plots) within each treatment rather than using the individual plot data. Because soil sampling was conducted before any treatment initiation, KSC values had nothing to do with the treatment; rather, KSC was a parameter used to describe the initial soil K stratification for each treatment. To study the influences of soil K stratification on critical leaf K concentrations, the entire data set for all treatments across the nine site-years was divided into the following two subsets: the treatments with KSC $\leq$ 2.00 and treatments with KSC $>$ 2.00. The choice of KSC = 2.00 as the dividing point assigned an approximately equal number of plots to both subgroups. Nonlinear regression of a quadratic-plateau model was conducted on the two data subsets separately to estimate the critical leaf K concentrations for maximum yield and concentrations of K, oil, and isoflavone in seed.

RESULTS AND DISCUSSION

Initial Soil Potassium Fertility

This study was conducted on soils representing a wide spectrum of soil K fertility levels (Table 1). Soil-test K concentrations were in the low range for all 3 yr at Paris, medium for all three seasons at Kirkton, but were categorized as very high in 1998, high in 1999, and medium in 2000 at Strathroy, according to the Ontario soil-test K interpretations (Ontario Ministry of Agriculture, Food, and Rural Affairs, 1997). Vertical soil-test K stratification before treatment initiation varied among plots within each site-year (data not presented) and differed among site-years. Initial soil-test K concentrations in the surface 0- to 5-cm layer were 2.1, 2.2, and 1.7 times higher than K levels present at the 10- to 20-cm depth at Kirkton, 2.3, 1.5, and 1.9 times greater than those in 10- to 20-cm at Strathroy, and 2.1, 1.8, and 2.5 times higher than those at the 10- to 20-cm depth at Paris in 1998, 1999, and 2000, respectively (Table 3). The sharp decrease in soil-test K with depth within the top 15 (or 20) cm of soil is a common phenomenon associated with no-till management (Buah et al., 2000; Holanda et al., 1998; Vyn and Janovicek, 2001).

Potassium Application and Placement Effects on Midseason Leaf Potassium Concentration

Kirkton

In the 1998 season, orthogonal contrasts indicated that K application significantly increased leaf K concentration in the fall disk system (Table 4). However, K application did not result in greater leaf K concentration under the no-tillage system. In both 1999 and 2000, adding K fertilizer significantly increased leaf K concentration in both tillage systems. However, significant leaf K effects due to banded versus broadcast K placements under either tillage system, or due to application timing

Table 3. Soil-test K levels and coefficient of variation for soil samples taken at four depth increments in nine site-years (1998–2000).

Location	Year	Soil depth	K concentration†	Coefficient of variation
		cm	mg L^{-1}	%
Kirkton	1998	0–5	135	18.4
		5–10	76	20.0
		10–20	65	24.2
		20–30	64	19.0
	1999	0–5	109	15.3
		5–10	61	20.3
		10–20	50	21.9
		20–30	45	24.5
	2000	0–5	122	28.0
		5–10	76	30.7
		10–20	71	21.8
		20–30	68	17.5
Strathroy	1998	0–5	229	22.1
		5–10	134	22.0
		10–20	101	24.1
		20–30	77	31.1
	1999	0–5	167	22.6
		5–10	122	21.8
		10–20	112	22.1
		20–30	95	20.1
	2000	0–5	138	25.6
		5–10	79	25.2
		10–20	71	24.9
		20–30	70	23.5
Paris	1998	0–5	51	16.1
		5–10	30	18.3
		10–20	25	21.2
		20–30	27	26.3
	1999	0–5	49	17.2
		5–10	30	12.2
		10–20	27	11.1
		20–30	29	16.1
	2000	0–5	85	28.2
		5–10	43	33.6
		10–20	34	33.6
		20–30	31	24.6

† K concentration and coefficient of variation for $n = 28$ at Kirkton and Strathroy, and $n = 32$ at Paris.

within the no-till system, were not observed in any of the 3 yr.

Strathroy

No significant leaf K responses to K application or placement under either tillage system, or application timing in no-till were observed in 1998 (Table 4). One possible explanation for the lack of significant leaf K responses to K treatments in this season was the very high initial soil-test K level (Table 1). In the 1999 season, leaf K concentration was increased by K application under both tillage systems. Banding (spring band in fall disk, or the average of fall band and spring band with no-till) was not superior to fall broadcast in either tillage system. In 2000, no significant leaf K responses to K application or placement under either tillage system, or application timing in no-till were observed. This was probably because the rainfall in June 2000 was 241 mm, three times greater than normal, and the high soil moisture levels may have greatly increased K availability in the soil, and thus enhanced plant K uptake even in the zero K plots.

Paris

Leaf K concentration in 1998 was affected by the K placement × row width interaction (Table 5). In 38-cm rows, significant gains in leaf K only occurred after banded K treatments, whereas, in 19-cm rows, only surface broadcasting of K resulted in significant increases in leaf K compared with zero K. The 1998 results showed that 38-cm banded K was more effective than surface broadcast K in increasing leaf K concentration for soybean seeded in 38-cm row width. Banding was not beneficial relative to broadcasting for soybean in 19-cm rows because at least half the rows were positioned 15 cm or

Table 4. Effects of K application, placement, and timing on leaf K concentration at Kirkton and Strathroy (1998–2000).

	Leaf K concentration					
	Kirkton			Strathroy		
Tillage and K placement	1998	1999	2000	1998	1999	2000
	g kg^{-1}					
No-till						
Fall band (a)	23.0	27.5	27.3	26.4	17.6	27.5
Spring band (b)	21.3	26.5	28.1	27.1	18.6	28.2
Fall broadcast (c)	22.3	28.8	27.1	27.5	17.8	27.3
Zero K (d)	22.0	22.5	23.9	26.9	12.6	25.4
Fall disk						
Spring band (e)	21.4	26.5	27.7	27.4	16.9	30.8
Fall broadcast (f)	20.7	26.8	26.5	27.4	17.6	29.0
Zero K (g)	19.2	23.1	24.4	26.1	14.8	27.9
Orthogonal contrasts‡	Significance for contrasts					
No-till						
Application [(a + b + c) vs. d]	ns†	**	***	ns	***	ns
Placement [(a + b) vs. c]	ns	ns	ns	ns	ns	ns
Application timing (a vs. b)	ns	ns	ns	ns	ns	ns
Fall disk						
Application [(e + f) vs. g]	*	*	**	ns	*	ns
Placement (e vs. f)	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Not significant at the 0.05 probability level.
‡ Application refers to the comparison of average over the K-fertilized treatments (spring band and fall broadcast in fall disk, or fall band, spring band, and fall broadcast with no-till) vs. Zero K. Placement indicates banding (spring band in fall disk, or fall band and spring band with no-till) vs. fall broadcast. Application timing refers to fall band vs. spring band in no-till.

Table 5. Effects of K application, placement, and row width on leaf K concentration at Paris (1998–2000).

Row width	K placement	Leaf K concentration 1998	1999	2000
cm			g kg^{-1}	
38	surface broadcast	17.8bc‡	14.1a	27.2a
	76-cm band	19.1b	18.0a	27.4a
	38-cm band	22.0a	17.7a	27.7a
	zero K	16.7c	10.5a	25.7b
19	surface broadcast	18.7a	13.9a	26.9b
	76-cm band	17.6ab	16.3a	26.5b
	38-cm band	18.0ab	18.4a	28.8a
	zero K	15.8b	12.2a	22.1c
Average				
38		18.9a	15.1a	27.0a
19		17.5b	15.2a	26.0a
	average			
	surface broadcast	18.2b	14.0b	27.1a
	76-cm band	18.4b	17.1a	27.0a
	38-cm band	20.0a	18.0a	28.3a
	zero K	16.3c	11.4c	23.9b
	statistics			
	K placement	**	***	***
	row width	*	ns†	ns
	K placement × row width	*	ns	*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Not significant at the 0.05 probability level.
‡ Means within each row width or each average in a column followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

more away from the fertilizer bands. In the 1999 season, K placement effects were not affected by row width. When averaged across three row widths, both band placement (38 or 76 cm apart) and surface broadcasting significantly increased leaf K concentration compared with zero K, but banding K fertilizer resulted in greater leaf K increases than surface broadcast K. In 2000, the interaction between K placement and row width was significant. Leaf K concentration was significantly increased by K application in both row widths regardless of placement method. No significant differences were observed between banded placement (38 or 76 cm apart) and surface broadcasting in 38-cm rows, but for soybean in 19-cm rows the 38-cm banded K treatment resulted in greater leaf K than 76-cm banded K and surface broadcast K.

In summary, band placement may be superior to surface broadcasting on low-testing soils. However, banding is not essential to improve soybean K nutrition on long-term no-till fields with medium to high soil-testing K levels—not even when soil K stratification is evident.

Critical Leaf Potassium Concentration for Midseason Soybean

The critical leaf K concentration at the initial flowering stage was 24.3 g kg^{-1} for the maximum seed yield of conservation-till soybean when the data from both tillage systems (no-till and fall disk) in all site-years were pooled (Fig. 1). When the data from only the no-till treatments (across years and locations) were used for analysis, the critical leaf K concentration was 25.9 g kg^{-1} for maximum yield (Table 6). These values are double the critical level of 12 g kg^{-1} that has been used in Ontario for soybean production systems regardless of

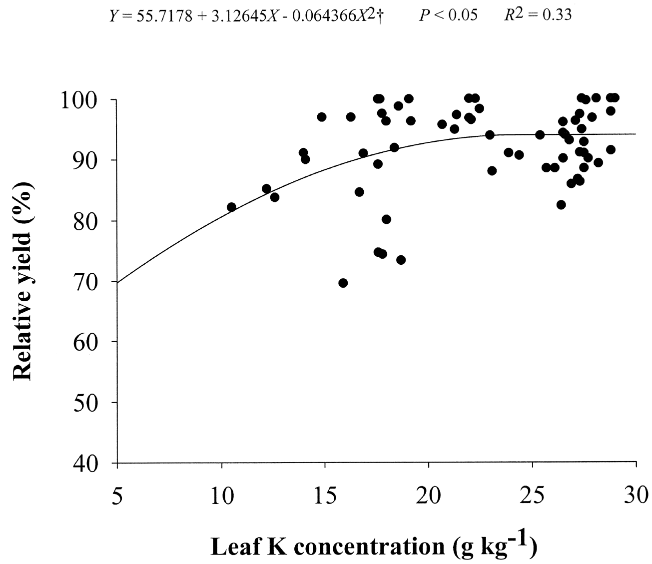

Fig. 1. A quadratic-plateau fit of relative soybean seed yield and leaf K concentration for all treatments across the nine site-years. †This quadratic equation applies only for X values less than the critical value at which the two portions (quadratic and plateau) of the model join.

tillage or soybean row width (Ontario Ministry of Agriculture, Food, and Rural Affairs, 1997). Our critical concentrations are also higher than the 21.1 g kg^{-1} average of the sufficiency leaf K range (17.1–25.0 g kg^{-1}) that was proposed by Small and Ohlrogge (1973) and the average of 21.3 g kg^{-1} of the sufficiency leaf K range (17.5–25.0 g kg^{-1}) reported in Georgia (Plank, 1979). Our critical concentrations are also greater than the critical leaf K values reported by Sartain et al. (1979) and by de Mooy and Pesek (1970) for soybean at developmental stages slightly later than the initial flowering stage. One contributing factor to the higher critical leaf K concentration for soybean under conservation tillage systems in this study may be vertical soil-test K stratification associated with conservation tillage. The use of narrow row widths instead of wide rows and the improvement in soybean yield may also contribute to the higher critical leaf K values in this study compared with the previously reported critical leaf K values.

The higher critical leaf K value we observed suggests that K fertilizer application based on maintaining the critical leaf K concentrations used in Ontario and in many states in the USA may result in yield losses. The previous critical leaf K values for soybean were generally estimated based on the data collected from soybean in conventional tillage (mainly moldboard plow) and wide-row production systems. It is apparent that the application of a higher critical leaf K concentration at midseason for soybean in conservation-till production systems with vertical soil K stratification may be required to deliver correct interpretations of leaf K analysis results to soybean producers. Indeed, the results of this study were instrumented in increasing leaf K concentration for soybean from the officially recommended 12.0 to 20.0 g kg^{-1} in 2003 (K. Reid, Secretary of Ontario Soil Management Research and Services Committee, personal communication, 2003).

Table 6. Quadratic-plateau regression analyses of relative seed yield and seed quality components with leaf K concentration across nine site-years of soybean in no-till systems.

Variable pair		Equation†	Significance	R^2	Critical value
Dependent	Independent				
					g kg^{-1}
Yield	Leaf K	$Y = 56.4402 + 2.88342X - 0.055726X^2$	*	0.26	25.9
Seed K	Leaf K	$Y = 52.9212 + 3.68606X - 0.075023X^2$	***	0.51	24.6
Oil	Leaf K	$Y = 93.5950 + 0.41819X - 0.007504X^2$	***	0.42	27.9
Isoflavone	Leaf K	$Y = 36.7293 + 4.74945X - 0.096703X^2$	***	0.30	24.6

* Significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.
† Each quadratic equation shown applies only for *X* values less than the critical value at which the two portion (quadratic and plateau) of the model join.

The critical leaf K concentration for maximum seed K concentration was 23.3 g kg^{-1} for soybean across the two conservation tillage systems (Fig. 2). The critical leaf K concentration for seed oil concentration was estimated to be 24.1 g kg^{-1}, and that for seed isoflavone concentration was estimated to equal 23.5 g kg^{-1} when the data were pooled across the two conservation tillage systems (Fig. 3 and 4). All these critical concentrations for maximum seed quality components were similar to those for maximum seed yield. When the data from the no-till treatments only were analyzed, critical leaf K concentrations were 24.6, 27.9, and 24.6 g kg^{-1} for maximum concentrations of K, oil, and isoflavone in seed, respectively (Table 6). Estimations of all these critical leaf K concentrations for seed quality components are helpful to soybean producers who aim to produce high-quality soybean for value-added markets.

It is encouraging that, in conservation tillage systems, the critical values of midseason leaf K for maximum yield and seed quality components we observed in this study were generally similar. This finding suggests that high seed yield and high seed quality components of soybean can be achieved simultaneously. In addition, our results showed that soybean under fall disk had slightly lower critical values of midseason leaf K than those under no-till management. This finding may be attributed to the decreased vertical soil-test K stratification resulting from soil mixing associated with fall disk tillage.

Impacts of Vertical Soil Potassium Stratification on Critical Leaf Potassium Concentration

Nonlinear regression analyses using a quadratic-plateau model showed that critical leaf K concentrations for maximum yield and concentrations of K, oil, and isoflavone in seed were higher in plots with a vertical soil K stratification coefficient greater than 2.00 than those in the plots with soil K stratification coefficient less than or equal to 2.00 when the data from both tillage systems were combined (Table 7). This suggests that the extent of vertical soil K stratification affects the critical leaf K concentrations for soybean at the initial flowering stage. The impacts of vertical soil K stratification on critical leaf K values may, at least in part, explain why there is a requirement for higher critical leaf K concentration by conservation-till soybean compared with soybean in conventional tillage.

Because vertical soil K stratification is commonly ob-

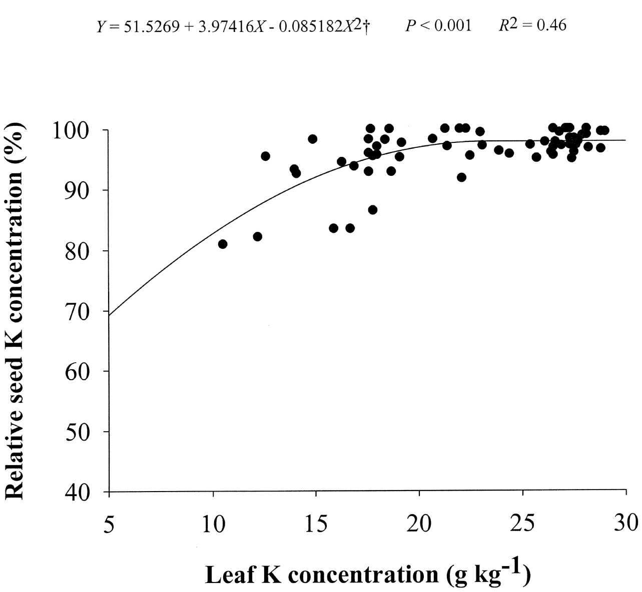

Fig. 2. A quadratic-plateau fit of relative soybean seed K concentration and leaf K concentration for all treatments across the nine site-years. †This quadratic equation applies only for *X* values less than the critical value at which the two portions (quadratic and plateau) of the model join.

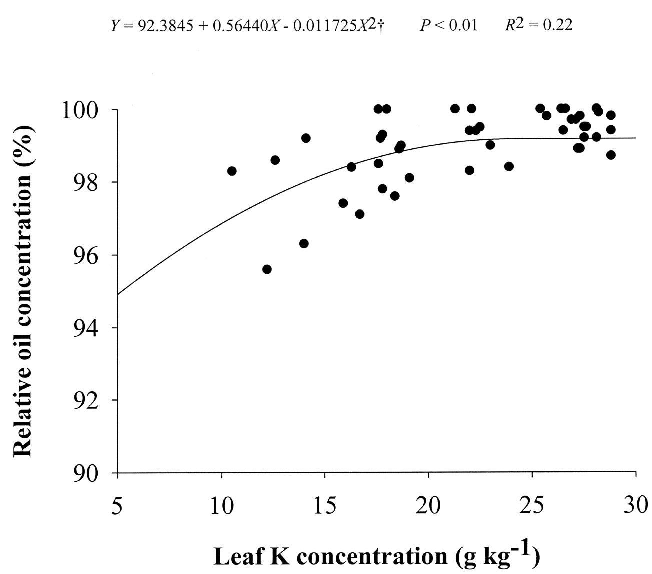

Fig. 3. A quadratic-plateau fit of relative soybean seed oil concentration and leaf K concentration for all treatments across the nine site-years. †This quadratic equation applies only for *X* values less than the critical value at which the two portions (quadratic and plateau) of the model join.

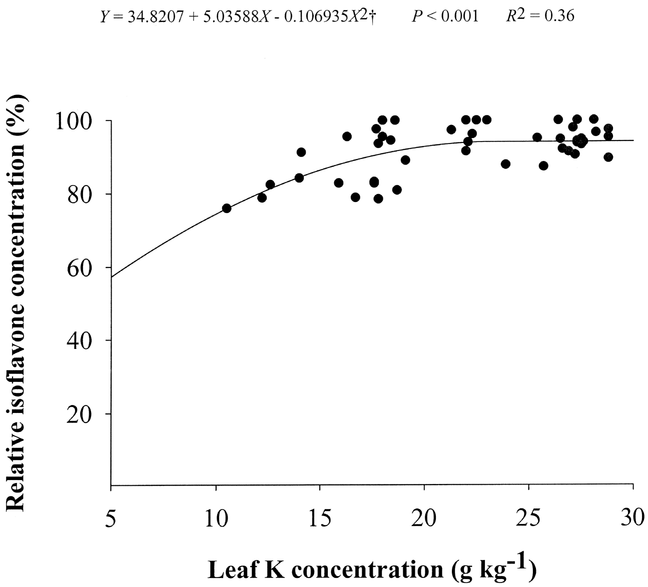

Fig. 4. A quadratic-plateau fit of relative soybean seed isoflavone concentration and leaf K concentration for all treatments across the nine site-years. †This quadratic equation applies only for *X* values less than the critical value at which the two portions (quadratic and plateau) of the model join.

served in fields under long-term conservation-till (particularly no-till) management (Holanda et al., 1998; Howard et al., 1999; Karathanasis and Wells, 1989; Yin and Vyn, 1999), and the crop acreages under conservation tillage systems have increased rapidly, it will be important to include the influences of vertical soil K stratification on critical leaf K values in plant K analysis interpretations.

This study included nine site-years totaling 264 plots. Therefore, the data from this study were a relatively small data set for arriving at a definitive critical leaf K concentration for changing plant tissue test interpretations in Ontario. In addition, the determination coefficients (R^2) of soybean yield versus leaf K were relatively low in this study although similar determination coefficients for the critical leaf K concentrations for corn were reported by Mallarino and Blackmer (1994). Nevertheless, the critical soybean leaf K value previously recommended in Ontario was undoubtedly too low.

CONCLUSIONS

Midseason leaf K concentrations were significantly increased by K application on soils with low- and medium-testing K. Band placement might be superior to surface broadcasting on low-testing soils. However, despite evident soil K stratification, banding was not required to improve soybean K nutrition in early flowering on long-term no-till fields with medium to high soil-testing K levels.

The critical leaf K concentration was estimated to be 24.3 g kg^{-1} for maximum seed yield of conservation-till soybean. This critical concentration is substantially greater than the critical values that are currently used in Ontario and higher than those being used in many U.S. Corn Belt states. Use of this new critical leaf K value for soybean in conservation-till production systems would reduce the chances of overestimating soybean K nutrition status and underestimating K fertilizer requirements for maximum yield relative to the older published critical leaf K values. Therefore, higher critical leaf K concentrations should be considered for adoption to accurately interpret the results of plant K analyses for conservation-till soybean.

With respect to the seed quality components investigated, the critical leaf K concentration was estimated to be 23.3 g kg^{-1} for maximum seed K concentration, 24.1 g kg^{-1} for seed oil concentration, and 23.5 g kg^{-1} for seed isoflavone concentration. It is encouraging that the critical levels of leaf K for maximum soybean yield and seed quality components were generally similar. This finding suggests that plant leaf K recommendations for maximum yield are compatible with those for maximum seed quality components.

Critical leaf K concentrations for maximum seed yield and concentrations of K, oil, and isoflavone in seed were higher in the plots that, before treatment initiation, had greater vertical soil-test K stratification relative to those with lower soil K stratification. This suggests that the degree of vertical soil-test K stratification before treatment initiation is one of the factors contributing to these higher critical leaf K concentrations for conservation-till soybean.

Table 7. Quadratic-plateau regression analyses of relative seed yield and seed quality components with leaf K concentration separated into vertical soil K stratification groups for the nine site-years of soybean in conservation tillage systems.

Variable pair		KSC†	Equation‡	Significance	R^2	Critical value
Dependent	Independent					
						g kg^{-1}
Yield	Leaf K	>2.00	$Y = -143.2000 + 20.34000X - 0.445286X^2$	***	0.33	22.8
		≤2.00	$Y = 29.0221 + 6.35247X - 0.166539X^2$	*	0.26	19.1
Seed K	Leaf K	>2.00	$Y = -39.4530 + 12.23000X - 0.272592X^2$	***	0.72	22.4
		≤2.00	$Y = 37.6398 + 5.70139X - 0.134225X^2$	***	0.67	21.2
Oil	Leaf K	>2.00	$Y = 78.1671 + 1.72948X - 0.034973X^2$	***	0.63	24.7
		≤2.00	$Y = 89.5116 + 0.89315X - 0.020655X^2$	**	0.32	21.6
Isoflavone	Leaf K	>2.00	$Y = -2.8940 + 7.51131X - 0.145252X^2$	***	0.46	25.9
		≤2.00	$Y = 13.1706 + 7.37786X - 0.168562X^2$	***	0.64	21.9

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† KSC, vertical stratification coefficient of soil-test K.
‡ Each quadratic equation shown applies only for *X* values less than the critical value at which the two portions (quadratic and plateau) of the model join.

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