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Postseason Diagnosis of Potassium Deficiency in Soybean Using Seed Potassium Concentration

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Soybean [*Glycine max* (L.) Merr.] seed nutrient concentrations may be useful for postseason diagnosis of nutrient deficiencies to identify reasons for lower-than-expected yields. Our objective was to determine the relationships between seed-K and soil-K concentrations and relative soybean yield and to develop potential seed-K concentration thresholds for diagnosis of K deficiency as a yield-limiting factor. Soil-test K and seed-K concentrations and yield data were collected from published and unpublished K fertilization research conducted in Arkansas (33 site-years), Indiana (1 site-year), Iowa (34 site-years), Missouri (1 site-year), Tennessee (6 site-years), Virginia (1 site-year), and Canada (24 site-years). Seed-K concentrations accounted for 66% of the variation in relative yield of soybean receiving no fertilizer K for Arkansas, 48% for Iowa, 78% for Canada, and 60% for North America from a database that included 100 site-years. The critical seed-K concentration ranges were 15.6 to 17.0 g K kg^{-1} for Arkansas, 17.4 to 20.0 g K kg^{-1} for Iowa, 14.6 to 16.2 g K kg^{-1} for Canada, and 16.5 to 17.7 g K kg^{-1} for North America. Seed-K concentrations below the lower threshold for North America accurately predicted positive yield responses to fertilizer K at 77% of the sites classified as deficient. The difference between seed-K concentration of soybean grown with and without fertilizer K decreased linearly as soil-K concentration increased and plateaued when soil-K concentration was $\geq$87, 139, 73, and 104 mg K kg^{-1} for Arkansas, Iowa, Canada, and North America, respectively. Results suggest that seed-K concentrations can be used to aid in the diagnosis of K deficiency at maturity.

Abbreviations: CL, confidence limits; LP, linear–plateau.

Core Ideas

- **Seed-K concentrations accounted for 60% of the variation in relative yield of unfertilized soybean for 100 site-years in North America.**
- **The proposed deficient seed-K concentration (<16.5 g kg^{-1}) identified fields that responded positively to fertilizer K 77% of the time.**
- **Seed-K concentration difference with and without fertilizer K decreased with the increase of soil K.**
- **Seed-K concentrations can help diagnose reasons for low yields and correct K deficiency for subsequent crops.**

Potassium is a common yield-limiting nutrient for soybean production. Seed yield increases from K fertilization of 5 to 25% are common (Clover and Mallarino, 2013; Coale and Grove, 1990; Mallarino et al., 1991; Parvej et al., 2015; Slaton et al., 2010, 2013), but soybean plants may not express K deficiency symptoms during the growing season. Trifoliolate leaf K concentration at the R1–R2 stage (Fehr et al., 1971) is currently the only information available to diagnose in-season K deficiency. The use of trifoliolate leaf K concentrations to diagnose K deficiency beyond the R2 stage is largely dependent on professional experience because critical tissue-K concentrations are not available for other growth stages. Based on our field observations of irrigated soybean in Arkansas, K deficiency symptoms do not commonly appear until mid to late reproductive growth (R5 stage and beyond). Although yield loss from K deficiency cannot likely be fully recovered at this late growth stage, proper diagnosis is important to correct the soil-K deficiency problem before the next crop.

Nutrient concentrations in mature plant tissues, including seed, can be used to identify nutrient deficiencies. For example, the NO_3–N concentration in a lower segment of mature corn (*Zea mays* L.) stalks is used to assess whether too little,

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adequate, or excessive fertilizer N was applied during the season (Binford et al., 1990, 1992; Brouder et al., 2000). The K concentrations of mature soybean seed might be useful in diagnosing late-season K deficiency and help explain lower-than-expected yields in the absence of K deficiency symptoms (e.g., hidden hunger). Small and Ohlrogge (1973) reported that soybean seed-K concentrations from 152 commercial fields were quite uniform, but micronutrient concentrations were variable enough that they expressed optimism for using seed analysis as a postseason diagnostic tool. For soybean, S (Hitsuda et al., 2004), Mn (Cox, 1968; Hitsuda et al., 2010; Parker et al., 1981), Zn (Hitsuda et al., 2010), B (Hitsuda et al., 2010), Cu (Hitsuda et al., 2010), and Mo (Lavy and Barber, 1963) deficiencies can reportedly be diagnosed from mature seed nutrient concentrations. Hitsuda et al. (2004) reported that seed-S concentration explained 74% of the variability in the relative yield for soybean grown in pots and soybean seed having >2.3 g S kg^{-1} was considered normal (i.e., nutritionally sufficient). Lavy and Barber (1963) observed that soybean grown on slightly acid soils did not respond to seed-applied Mo when the planted seed contained >1.6 mg Mo kg^{-1} and concluded that mature soybean seed-Mo concentration could be used to assess whether the soil contained sufficient available Mo. Mallarino and Higashi (2009) reported no significant relationship between relative corn yield or soil-test K with absolute corn grain-K concentration, but a significant relationship was found between relative grain K and soil-test K. We could find no other research relating seed-K concentration to soil-test K or crop yield for postseason diagnosis of K deficiency in soybean or any other crop.

Soybean seed-K concentrations are reportedly influenced by K availability and may be increased by K fertilization. Changes in seed-K concentrations due to fertilization most often occur when seed yield also increases from K fertilization (Coale and Grove, 1990; Clover and Mallarino, 2013; Parvej et al., 2015; Slaton et al., 2013; Terman, 1977; Yin and Vyn, 2002). However, seed-K concentration increases from K fertilization in the absence of a yield benefit have also been reported (Clover and Mallarino, 2013; Parvej et al., 2015; Slaton et al., 2013). Potassium fertilization can increase soybean seed-K concentrations more than 50% (Sale and Campbell, 1987), but increases of 5 to 20% are more typical (Bellaloui et al., 2013; Clover and Mallarino, 2013; Nelson et al., 2005; Oltmans and Mallarino, 2015; Parsons et al., 2007; Parvej et al., 2015; Vyn et al., 2002; Yin and Vyn, 2003). The trend for seed K to increase in fields where yield is also increased by fertilizer K suggests that relative soybean yield and seed-K concentration may be correlated.

Our primary research objectives were to determine whether a relationship exists between relative soybean yield and seed-K concentration and, if a relationship exists, to define critical seed-K concentration thresholds for identifying K deficiency. Our secondary objective was to evaluate whether or not seed-K concentration increases from K fertilization only when soil-K availability is low. We predicted that (i) soybean relative seed yield and seed-K concentration would be positively correlated, (ii) soybean seed could be used to diagnose K deficiency, and (iii) soybean seed-K concentration would increase as soil-test K increased because research has shown soybean seed-K concentration is often influenced by K fertilization.

MATERIALS AND METHODS

Experimental Sites and Treatments

Unpublished data and results from published research with objectives investigating soybean response to K fertilization were used to achieve the stated objectives. The final dataset included a total of 100 site-years of results. The dataset included 33 observations from Arkansas, 34 observations from Iowa, 24 site-years from Canada, and another nine observations from several other soybean-producing states within the United States (Table 1). Only field research results were included in the dataset. Among the 33 observations from Arkansas, nine were from unpublished research. Selected information summarized in Table 1 includes site number, geographic location, soil series, soil group, cultivar, previous crop, row spacing, and irrigation method, if available. Seed-K concentration and soybean yield response to K fertilization from replicated research were required for the information to be included in the dataset. The relative seed yield of soybean receiving no fertilizer K for each site-year was calculated by dividing the mean yield of soybean receiving no fertilizer K by the highest mean yield of soybean receiving fertilizer K and multiplying by 100. Note that this method allows for the calculation of relative yields greater than 100%, which would indicate that soybean receiving no fertilizer K produced a higher numerical yield than soybean receiving fertilizer K and therefore could indicate a possible yield decrease from fertilization.

Information on soil pH, soil-test K concentration, and yield and seed-K concentration responses to fertilizer K are summarized in Table 2. The seed-K concentrations listed in Table 2 represent soybean receiving no fertilizer K and the greatest numerical seed-K concentration of soybean receiving fertilizer K. Soil chemical properties, including soil-test K concentration, were not listed for all site-years obtained from the literature. For site-years that had soil-test K concentration, soil K was extracted with either Mehlich-1 (Sims, 1989), Mehlich-3 (Helmke and Sparks, 1996), or NH_4OAc (Warncke and Brown, 1998) procedures using air- or oven-dry soil samples that represented the 0- to 10-cm (Sites 1–33, 73–89, and 98) or the 0- to 15-cm (all other sites) soil depths before establishing the field trial. Soil-test K concentrations determined only by Mehlich-3 or NH_4OAc methods were used to evaluate the correlations between relative soybean yield and soil-test K concentration and between seed-K and soil-test K concentrations because these two methods have consistently been shown to extract comparable amounts of soil K (Beegle and Oravec, 1990) and because the same soil-K concentration thresholds are often used for making fertilizer-K recommendations (Mallarino et al., 2013). The Mehlich-1 method frequently extracts different amounts of soil K than the Mehlich-3 (Sikora, 2004) and NH_4OAc (Gartley et al., 2002) methods. Although soil sample depths varied among sites, soil-K concentrations were not adjusted for the different depths. In Arkansas, Mehlich-3–extractable K from the 0- to 10-m depth is, on average, 13 mg K kg^{-1} greater than in samples collected from the 0- to 15-cm depth (N.A. Slaton, unpublished data, 2007).

The amount of detail describing soybean seed analysis for each site-year obtained from the literature differs (see references

Table 1. Selected soil and agronomic information of each site.

Site	Location	Soil classification: Series	Group†	Cultivar	Previous crop	Row spacing	Irrigation	References
						cm		
1	Arkansas	Calhoun	TG	Armor 47F8	soybean	38	irrigated	unpublished data (2009)
2	Arkansas	Calhoun	TG	Armor 48R40	rice	38	irrigated	unpublished data (2012)
3	Arkansas	Calhoun	TG	Armor 53R15	rice	38	irrigated	unpublished data (2012)
4	Arkansas	Dewitt	TA	Armor 48R40	soybean	18	irrigated	unpublished data (2013)
5	Arkansas	Calhoun	TG	Armor 48R40	rice	38	irrigated	unpublished data (2013)
6	Arkansas	Calhoun	TG	Armor 53R15	rice	38	irrigated	unpublished data (2013)
7	Arkansas	Dewitt	TA	Armor 47R13	rice	18	irrigated	unpublished data (2014)
8	Arkansas	Calhoun	TG	Armor 48R66	rice	38	irrigated	unpublished data (2014)
9	Arkansas	Calhoun	TG	Armor 55R22	rice	38	irrigated	unpublished data (2014)
10	Arkansas	Dewitt	TA	Armor 55R22	soybean	18	irrigated	Fryer (2015)
11	Arkansas	Sharkey/Desha	CE/VH	Armor 55R22	soybean	97	irrigated	Fryer (2015)
12	Arkansas	Desha	VH	Armor 55R22	soybean	97	irrigated	Fryer (2015)
13	Arkansas	Foley/Calhoun	GN/TG	Armor X1307	rice	38	irrigated	Fryer (2015)
14	Arkansas	Sharkey/Steele	CE/AU	Armor X1307	soybean	97	irrigated	Fryer (2015)
15	Arkansas	Calloway	AF	Armor 48R40	soybean	38	irrigated	Fryer (2015)
16	Arkansas	Calloway	AF	Armor X1316	soybean	38	irrigated	Fryer (2015)
17	Arkansas	Calloway	AF	Armor X1307	rice	38	irrigated	Fryer (2015)
18	Arkansas	Dewitt	TA	Armor 47R13	soybean	76	irrigated	Fryer (2015)
19	Arkansas	Sharkey/Desha	CE/VH	Armor 55R22	soybean	97	irrigated	Fryer (2015)
20	Arkansas	Sharkey/Desha	CE/VH	Armor 55R22	soybean	97	irrigated	Fryer (2015)
21	Arkansas	Sharkey	CE	Halo 4:99	soybean	97	irrigated	Fryer (2015)
22	Arkansas	Calloway	AF	Armor 55R22	soybean	38	irrigated	Fryer (2015)
23	Arkansas	Calloway	AF	Armor 55R22	soybean	38	irrigated	Fryer (2015)
24	Arkansas	Calloway	AF	Pioneer 94Y82	soybean	76	irrigated	Fryer (2015)
25	Arkansas	Calloway	AF	Armor 49R56	soybean	38	irrigated	Fryer (2015)
26	Arkansas	Hillemann	GN	Asgrow 5501	rice	18	irrigated	Slaton et al. (2013)
27	Arkansas	Hillemann	GN	UA 4805	rice	18	irrigated	Slaton et al. (2013)
28	Arkansas	Calhoun	TG	Armor 47G7	soybean	38	irrigated	Slaton et al. (2013)
29	Arkansas	Sharkey	CE	HBK 5525	soybean	48	irrigated	Slaton et al. (2013)
30	Arkansas	Dewitt	TA	Armor 47F8	fallow	76	irrigated	Slaton et al. (2013)
31	Arkansas	Henry	TF	HBK 4727	rice	38	irrigated	Slaton et al. (2013)
32	Arkansas	Calhoun	TG	Armor 47F8	soybean	38	irrigated	Slaton et al. (2013)
33	Arkansas	Calhoun	TG	Armor 47F8	soybean	38	irrigated	Slaton et al. (2013)
34	Iowa	Canisteo	TE	Pioneer 92M70	corn	–	rainfed	Clover and Mallarino (2013)
35	Iowa	Canisteo	TE	Prairie Brand 2643	corn	–	rainfed	Clover and Mallarino (2013)
36	Iowa	Webster	TE	Asgrow 2601	corn	–	rainfed	Clover and Mallarino (2013)
37	Iowa	Kenyon	TH	Crows 2130	corn	–	rainfed	Clover and Mallarino (2013)
38	Iowa	Canisteo	TE	Latham 2038	corn	–	rainfed	Clover and Mallarino (2013)
39	Iowa	Primghar	AH	Kruger 223	corn	–	rainfed	Clover and Mallarino (2013)
40	Iowa	Primghar	AH	Kruger 223	corn	–	rainfed	Clover and Mallarino (2013)
41	Iowa	Nira	AA	Asgrow 3602	corn	–	rainfed	Clover and Mallarino (2013)
42	Iowa	Mahaska	ATA	Asgrow 3302	corn	–	rainfed	Clover and Mallarino (2013)
43	Iowa	Clarion	TH	Asgrow 2601	corn	–	rainfed	Clover and Mallarino (2013)
44	Iowa	Nicollet	AH	Prairie Brand 2994	corn	–	rainfed	Clover and Mallarino (2013)
45	Iowa	Nicollet	AH	Prairie Brand 2994	corn	–	rainfed	Clover and Mallarino (2013)
46	Iowa	Webster	TE	Pioneer 92M30	corn	–	rainfed	Clover and Mallarino (2013)
47	Iowa	Clyde	TE	Crows 2130	corn	–	rainfed	Clover and Mallarino (2013)
48	Iowa	Nicollet	AH	Cropland 2089	corn	–	rainfed	Clover and Mallarino (2013)

continued on next page.

Table 1. continued.

Site	Location	Soil classification Series	Group†	Cultivar	Previous crop	Row spacing	Irrigation	References
49	Iowa	Galva	TH	Kruger 223	corn	–	rainfed	Clover and Mallarino (2013)
50	Iowa	Galva	TH	Kruger 223	corn	–	rainfed	Clover and Mallarino (2013)
51	Iowa	Taintor	VA	Pioneer 93M42	corn	–	rainfed	Clover and Mallarino (2013)
52	Iowa	Mahaska	ATA	Pioneer 93M42	corn	–	rainfed	Clover and Mallarino (2013)
53	Iowa	Clarion	TH	Dekalb 26–52	corn	–	rainfed	Clover and Mallarino (2013)
54	Iowa	Clarion	TH	Pioneer 92M61	corn	76	rainfed	Oltmans and Mallarino (2015)
55	Iowa	Kenyon	TH	NK S21-N6	corn	76	rainfed	Oltmans and Mallarino (2015)
56	Iowa	Floyd	APH	Asgrow 2108	corn	76	rainfed	Oltmans and Mallarino (2015)
57	Iowa	Canisteo	TE	Kruger 201	corn	76	rainfed	Oltmans and Mallarino (2015)
58	Iowa	Webster	TE	Kruger 201	corn	76	rainfed	Oltmans and Mallarino (2015)
59	Iowa	Webster	TE	Stine 1923	corn	76	rainfed	Oltmans and Mallarino (2015)
60	Iowa	Haig	VA	Pioneer 93M11	corn	76	rainfed	Oltmans and Mallarino (2015)
61	Iowa	Grundy	ATA	Pioneer 93M11	corn	76	rainfed	Oltmans and Mallarino (2015)
62	Iowa	Grundy	ATA	FS 37A02	corn	76	rainfed	Oltmans and Mallarino (2015)
63	Iowa	Taintor	VA	Pioneer 92Y80	corn	76	rainfed	Oltmans and Mallarino (2015)
64	Iowa	Taintor	VA	Asgrow 3402	corn	76	rainfed	Oltmans and Mallarino (2015)
65	Iowa	Taintor	VA	Pioneer 93Y40	corn	76	rainfed	Oltmans and Mallarino (2015)
66	Iowa	Marshall	TH	Pioneer 93M11	corn	76	rainfed	Oltmans and Mallarino (2015)
67	Iowa	Exira	TH	NK S28-B4	corn	76	rainfed	Oltmans and Mallarino (2015)
68	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Vyn et al. (2002)
69	Canada	–	THF/THT	NK S19–90/NK S08–80	corn	38	rainfed	Vyn et al. (2002)
70	Canada	–	THF	OAC Bayfield/FL 2801R	wheat	38	rainfed	Vyn et al. (2002)
71	Canada	–	THF	FL 2801R	corn	19	rainfed	Vyn et al. (2002)
72	Canada	Listowel	THF	FL 2801R	corn	38	rainfed	Vyn et al. (2002)
73	Canada	Listowel	THF	First Line 2801R	corn	38	rainfed	Yin and Vyn (2002)
74	Canada	Listowel	THF	First Line 2801R	corn	38	rainfed	Yin and Vyn (2002)
75	Canada	Listowel	THF	First Line 2801R	corn	38	rainfed	Yin and Vyn (2002)
76	Canada	Listowel	THF	First Line 2801R	corn	38	rainfed	Yin and Vyn (2002)
77	Canada	Toledo	THT	Pioneer 9163	corn	50	rainfed	Yin and Vyn (2002)
78	Canada	Toledo	THT	Pioneer 9163	corn	50	rainfed	Yin and Vyn (2002)
79	Canada	Toledo	THT	Pioneer 9163	corn	50	rainfed	Yin and Vyn (2002)
80	Canada	Toledo	THT	Pioneer 9163	corn	50	rainfed	Yin and Vyn (2002)
81	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
82	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
83	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
84	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
85	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
86	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
87	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
88	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
89	Canada	–	THF	OAC Bayfield	wheat	19–76	rainfed	Yin and Vyn (2003)
90	Canada	Timberland	–	Dekalb 2601R	wheat	76	rainfed	Parsons et al. (2007)
91	Canada	Timberland	–	Dekalb 2601R	corn	76	rainfed	Parsons et al. (2007)
92	Tennessee	Memphis	–	Pioneer 94M80	soybean	76	rainfed	Bellaloui et al. (2013)
93	Tennessee	Memphis	–	Pioneer 94M80	soybean	76	rainfed	Bellaloui et al. (2013)
94	Tennessee	Memphis	–	Pioneer 94M80	soybean	76	rainfed	Bellaloui et al. (2013)
95	Tennessee	Dexter	–	Pioneer 94M80	soybean	76	rainfed	Bellaloui et al. (2013)
96	Tennessee	Dexter	–	Pioneer 94M80	soybean	76	rainfed	Bellaloui et al. (2013)
97	Tennessee	Dexter	–	Pioneer 94M80	soybean	76	rainfed	Bellaloui et al. (2013)
98	Indiana	Toronto-Millbrook	UEN/UEP	Becks 336 NRR	corn	19	rainfed	Fernández et al. (2008)
99	Missouri	Mexico	VE	Asgrow 3701	soybean	19	rainfed	Nelson et al. (2005)
100	Virginia	Davidson	RK	York	soybean	75	rainfed	Jones et al. (1977)

† AA, Aquic Argiudoll; AF, Aquic Fraglossudalf; AH, Aquic Hapludoll; APH, Aquic Pachic Hapludoll; ATA, Aquertic Argiudoll; AU, Aquic Udifluvent; CE, Chromic Epiaquert; GN, Glossic Natraqualf; RK, Rhodic Kandiudult; TA, Typic Albaqualf; TE, Typic Endoaquoll; TF, Typic Fragiaqualf; TG, Typic Glossaqualf; TH, Typic Hapludoll; UEN, Udollic Endoaqualf; UEP, Udollic Epiaqualf; VA, Vertic Argiaquoll; VE, Vertic Epiaqualf; VH, Vertic Hapludoll.

Table 2. Selected soil chemical property and relative seed yield means of soybean that received no fertilizer K and actual yield and seed-K concentration means of soybean as affected by K fertilization for each site.

Site†	Soil pH	Soil-test K conc.‡§	RSY¶	Seed yield			Seed-K concentration		
				No K	+K#	Response††	No K	+K#	Response††
		mg K kg^{-1}	%	— kg ha^{-1} —			— g K kg^{-1} —		
1	8.0	83	64.7	2660	4111	yes	13.1	17.8	yes
2	7.6	61	91.3	4340	4754	yes	16.2	22.2	yes
3	7.6	61	93.6	3391	3623	yes	18.4	21.7	yes
4	6.2	80	79.4	1862	2344	yes	16.7	19.1	yes
5	7.6	67	79.5	2858	3596	yes	13.1	17.0	yes
6	7.6	67	79.1	3117	3943	yes	15.0	18.9	yes
7	5.5	99	87.3	4465	5114	yes	15.0	16.5	yes
8	7.9	76	85.4	3006	3518	yes	15.4	18.7	yes
9	7.9	76	81.9	3710	4528	yes	15.7	17.2	yes
10	6.4	102	97.2	4185	4306	no	16.9	16.6	no
11	7.5	353	97.9	5073	5184	no	16.4	16.6	no
12	7.2	157	100.1	5534	5526	no	15.6	16.1	no
13	5.5	131	97.8	4813	4920	no	16.1	16.8	no
14	6.4	330	97.8	4887	4998	no	17.3	16.6	no
15	6.9	88	88.7	3292	3710	yes	14.7	16.0	yes
16	7.0	94	89.3	3178	3559	yes	15.2	16.5	yes
17	7.2	96	90.4	5191	5742	yes	15.4	15.9	no
18	6.2	72	93.3	3647	3908	no	14.6	17.8	yes
19	7.6	201	96.9	4398	4539	no	17.3	18.2	yes
20	7.3	146	90.6	3638	4013	yes	18.5	18.4	no
21	7.2	267	98.1	3630	3699	no	18.4	19.0	no
22	6.9	78	100.6	3980	3955	no	16.3	17.1	yes
23	7.6	76	94.2	4029	4278	no	17.1	18.2	yes
24	7.3	161	96.9	4603	4748	no	18.9	19.1	no
25	7.2	60	77.3	3410	4410	yes	13.6	16.5	yes
26	8.0	103	87.6	4375	4992	yes	14.5	15.4	yes
27	7.8	135	87.4	4109	4702	yes	14.6	16.4	yes
28	8.2	105	87.2	3962	4543	yes	14.1	15.5	yes
29	7.7	408	99.4	3661	3683	no	20.5	21.2	yes
30	6.2	115	95.7	3981	4162	yes	15.5	16.1	no
31	7.2	87	89.8	3978	4430	yes	14.9	15.4	yes
32	7.9	95	91.3	3881	4249	yes	15.8	16.4	no
33	7.7	90	99.8	3852	3861	no	18.4	18.2	no
34	6.3	163	103.3	3720	3600	no	20.5	21.3	no
35	6.6	139	91.6	3600	3930	yes	18.8	19.5	no
36	7.3	153	86.2	2310	2680	yes	14.1	17.6	yes
37	6.7	170	100.7	4300	4270	no	17.8	18.4	yes
38	6.7	138	96.0	3350	3490	no	18.8	19.4	no
39	6.2	213	96.9	3720	3840	no	18.3	19.5	yes
40	6.2	154	93.2	3020	3240	yes	18.2	19.7	yes
41	6.0	148	103.0	4800	4660	no	18.7	19.7	no
42	6.3	130	89.0	3080	3460	yes	16.3	18.1	yes
43	6.7	102	92.5	2100	2270	no	17.4	20.3	yes
44	7.2	150	96.5	2760	2860	no	23.5	24.3	no
45	7.6	234	100.0	2890	2890	no	21.5	21.9	no
46	6.6	133	84.9	2860	3370	yes	16.6	17.8	yes
47	6.7	196	100.9	4400	4360	no	19.6	20.4	no
48	5.7	162	98.8	4120	4170	no	20.7	22.5	yes
49	6.3	173	98.4	2430	2470	no	18.0	18.1	no
50	6.5	170	92.2	3570	3870	yes	20.0	21.2	yes
51	6.4	141	94.9	3930	4140	no	15.8	16.8	yes
52	6.2	134	99.5	4270	4290	no	20.2	20.8	no
53	6.7	117	89.2	2890	3240	yes	16.8	17.4	no

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Table 2. continued.

Site†	Soil pH	Soil-test K conc.‡§	RSY¶	Seed yield			Seed-K concentration		
				No K	+K#	Response††	No K	+K#	Response††
54	5.5	86	93.8	3920	4180	yes	18.4	19.8	yes
55	6.2	117	100.2	4640	4630	no	18.8	20.1	no
56	6.6	128	102.6	4390	4280	no	18.6	19.3	no
57	7.4	140	100.3	3750	3740	no	18.5	18.9	yes
58	6.9	188	92.2	3190	3460	yes	18.8	19.6	no
59	6.9	119	83.4	2920	3500	yes	15.0	16.7	yes
60	6.3	96	97.3	4300	4420	no	18.4	20.0	yes
61	6.9	97	90.3	4390	4860	yes	16.7	18.8	no
62	6.9	97	84.4	3190	3780	yes	16.2	18.1	yes
63	5.9	115	100.3	3880	3870	no	18.9	18.8	no
64	6.2	215	111.0	4930	4440	no	19.1	20.5	yes
65	6.2	133	121.4	4540	3740	no	15.9	16.8	no
66	6.9	166	100.0	4690	4690	no	21.1	21.8	yes
67	6.3	227	100.6	4880	4850	no	16.7	17.9	no
68	6.3	42	90.9	2390	2630	yes	14.9	17.0	yes
69	7.2	128	99.4	3460	3480	no	17.6	17.9	no
70	7.2	85	98.1	3110	3170	no	17.6	17.9	no
71	6.1	54	95.0	2470	2600	no	15.3	16.8	yes
72	6.8	88	93.3	3470	3720	yes	16.5	17.3	yes
73	–	84	96.9	3490	3600	no	17.0	17.5	yes
74	–	84	98.6	3520	3570	no	17.2	17.3	no
75	–	84	95.1	3530	3710	no	16.4	16.7	no
76	–	84	97.0	3510	3620	no	16.3	16.8	yes
77	–	143	101.0	3160	3130	no	18.9	18.9	no
78	–	143	99.4	3130	3150	no	18.8	18.9	no
79	–	143	95.3	2820	2960	no	16.7	17.0	yes
80	–	143	98.0	2880	2940	no	16.8	16.9	yes
81	6.6	41	79.5	1550	1950	yes	13.8	17.0	yes
82	6.4	40	87.1	2220	2550	yes	13.6	16.4	yes
83	6.0	64	100.4	2640	2630	no	17.3	18.1	yes
84	6.6	41	84.6	2640	3120	yes	14.2	17.0	yes
85	6.4	40	82.2	2220	2700	yes	13.2	16.2	yes
86	6.0	64	89.1	2780	3120	no	17.4	18.2	yes
87	6.6	41	87.2	2180	2500	yes	14.2	16.4	yes
88	6.4	40	87.8	2300	2620	yes	13.4	16.0	yes
89	6.0	64	99.3	3030	3050	no	16.8	18.2	yes
90	6.6	102	63.6	1400	2200	yes	12.7	13.8	yes
91	6.6	102	57.9	1100	1900	yes	12.9	13.4	no
92	–	108	106.0	2454	2316	no	18.9	19.5	yes
93	–	108	92.8	2303	2482	no	19.9	20.5	yes
94	–	108	99.4	1073	1080	no	16.5	17.3	yes
95	–	–	95.2	2333	2450	yes	19.6	20.7	yes
96	–	–	98.3	2772	2821	no	20.9	21.0	no
97	–	–	84.2	1053	1250	yes	15.8	17.3	yes
98	6.1	64	72.4	2469	3410	yes	14.8	15.3	yes
99	7.2	73	53.9	1852	3437	yes	13.9	16.8	yes
100	6.9	30	48.7	1596	3276	yes	15.7	18.2	yes

† The literature reference for each site is listed in Table 1.

‡ Soil samples for soil-test K concentration were collected from 0- to 10-cm soil depth for Sites 1–33, 73–89, and 98 and from 0- to 15-cm soil depth for Sites 34–72, 90–97, and 99. No soil sample depth was provided for Site 100.

§ Soil-test K was extracted by Mehlich-3 for Sites 1–33 and 90–91, NH_4OAc for Sites 34–89 and 98–99, and Mehlich-1 for Sites 92–97 and 100. No soil-test K information for Sites 95–97 was provided.

¶ Relative seed yield of the plants without K fertilizer was calculated by dividing the untreated control yield (numerator) by the highest yield produced by soybean receiving fertilizer K (denominator) and multiplying by 100.

The seed yield and seed-K concentration listed for each site represent the greatest numerical seed actual yield and seed-K concentration among K fertilization treatments.

†† Seed yield and seed-K concentration were significantly increased by K fertilization at the 0.10 probability level for Sites 1–67 and 0.05 probability level for Sites 68–100.

listed in Table 1). In general, a subsample of harvested seed was oven-dried and ground. Seed or ash was digested, and the sample was analyzed for K concentration using spectroscopy. Although the procedures for processing and analyzing seed varied among the studies, the assumption made for this analysis is that the differences in final seed-K concentrations caused by different analytical methods were relatively small.

Statistical Analysis

The relationships between relative seed yield and seed-K concentration of soybean receiving no fertilizer K were assessed with linear, quadratic, and linear–plateau (LP) models using the GLM or NLIN procedures of SAS (Version 9.4, SAS Institute). The LP model consistently had the lowest residual sums of squares and the highest R^2 values among the models evaluated. Therefore, relationships defined only by the LP model will be presented. The relationships between relative yield and seed-K concentration were evaluated for each geographic location having enough sites for meaningful analysis (e.g., 33 site-years for Arkansas, 34 site-years for Iowa, and 24 site-years for Canada) and for all geographic locations grouped together (e.g., North America = 100 site-years) (Tables 1 and 2). The relationships between seed-K and soil-test K concentrations and seed-K difference (seed K of soybean that received fertilizer K minus seed K of soybean that received no fertilizer K) and soil-test K concentration for Arkansas, Iowa, Canada, and for the North America were evaluated using the same statistical procedures. The Studentized residuals distribution for each regression was tested to identify outliers. When the Studentized residual was greater than ±2.5 for a site, the data point was removed, and the regression was rerun after removing the outliers.

For each geographic area, seed-K concentration thresholds for the deficient, low (e.g., critical range), and sufficient seed-K levels were calculated using the 95% confidence limits (CL) of the LP model join point. Seed-K concentrations greater than the upper critical range threshold were defined as sufficient, and concentrations below the lower critical range threshold were considered deficient. Seed-K concentrations within the critical range (95% CL) were considered low.

RESULTS AND DISCUSSION

Relationships between Relative Seed Yield and Seed Potassium Concentration

Arkansas

The average seed yield of irrigated soybean at the 33 Arkansas sites was 3900 kg ha^{-1} for soybean receiving no fertilizer K and 4292 kg ha^{-1} for soybean receiving fertilizer K. Irrigated soybean receiving no fertilizer K had relative yields that ranged from 64.7 to 100.6% and seed-K concentrations from 13.1 to 20.5 g K kg^{-1} (Table 2; Fig. 1a). The initial model that considered all site-years showed that seed K plateaued at 16.0 g K kg^{-1}, had a 95% CL range of 15.1 to 16.9 g K kg^{-1}, and explained 55% of the relative yield variability. The final regression between relative soybean yield and seed-K concentration was determined using 32 of the 33 sites because Site 4 was identified as an outlier and was omitted from the regression (Tables 1 and 2). Soybean seed-K concentration accounted for 66% of the variability in relative yield among the 32 sites (Table 3; Fig. 1a). Relative yield increased linearly as seed-K concentration increased and plateaued when the seed-K concentrations reached 16.3 g K kg^{-1} (Table 3). The critical range as defined by the 95% CL of the join point corresponded to seed-K concentrations of 15.6 to 17.0 g K kg^{-1}. Seed-K concentrations $\leq$15.5 g K kg^{-1} were deficient, and $\geq$17.1 g K kg^{-1} were sufficient. The accuracy of the deficient, low, and sufficient seed-K levels was assessed by determining the percentage of positive yield responses that occurred within each seed-K level (Table 4; Fig. 1a). Among the 33 Arkansas sites, significant yield responses to fertilizer K were measured at 14 of 15 sites with deficient seed-K concentrations (for the seed from soybean that received no fertilizer K), four of nine sites with low seed K, and two of nine sites that had sufficient seed-K levels (Table 4). The absolute yield difference attributed to fertilizer K was greatest for soybean having deficient seed K and least for sites with sufficient seed-K concentrations (Table 4).

Iowa

Unirrigated soybean receiving no fertilizer K at 34 sites in Iowa had relative yields of 83.4 to 121.4% and seed-K concentrations of 14.1 to 23.5 g K kg^{-1} (Table 2; Fig. 1b). The actual seed yields of soybean grown with and without fertilizer K averaged 3698 and 3810 kg ha^{-1}, respectively, across the 34 sites. The initial model that considered all Iowa site-years explained only 16% of the relative yield variability and predicted that seed K plateaued at 19.1 g K kg^{-1}. Site 65 was identified as an outlier and omitted from the final dataset used to regress relative yield with seed-K concentration. Seed-K concentration explained 48% of the variability in relative yield among the 33 Iowa sites (Table 3; Fig. 1b). Relative soybean yield plateaued when seed-K concentration was 18.7 g K kg^{-1}. The predicted critical range of seed-K concentration was 17.4 to 20.0 g K kg^{-1}. The defined seed-K levels were reasonably accurate in correctly identifying whether soybean benefited from fertilizer K. Soybean at 7 of 10 sites having deficient seed-K concentrations benefited from fertilizer K with an 8% mean seed yield increase (Table 4).

Canada

Seed yield across the 24 sites in Canada averaged 2708 kg ha^{-1} when no fertilizer K was applied and 2943 kg ha^{-1} when soybean received fertilizer K, an 8.7% difference (Table 2). Soybean receiving no fertilizer K produced relative yields of 57.9 to 101.0% of the yield produced by soybean receiving fertilizer K and had seed-K concentrations ranging from 12.7 to 18.9 g K kg^{-1} (Fig. 1c). The LP model, fit across 23 sites (Site 91 removed as an outlier), explained 78% of the variability in relative soybean yield (Table 3). The predicted critical seed-K concentration range was 14.6 to 16.2 g K kg^{-1}. The accuracy of the defined categories for identifying K responsive sites was numerically similar

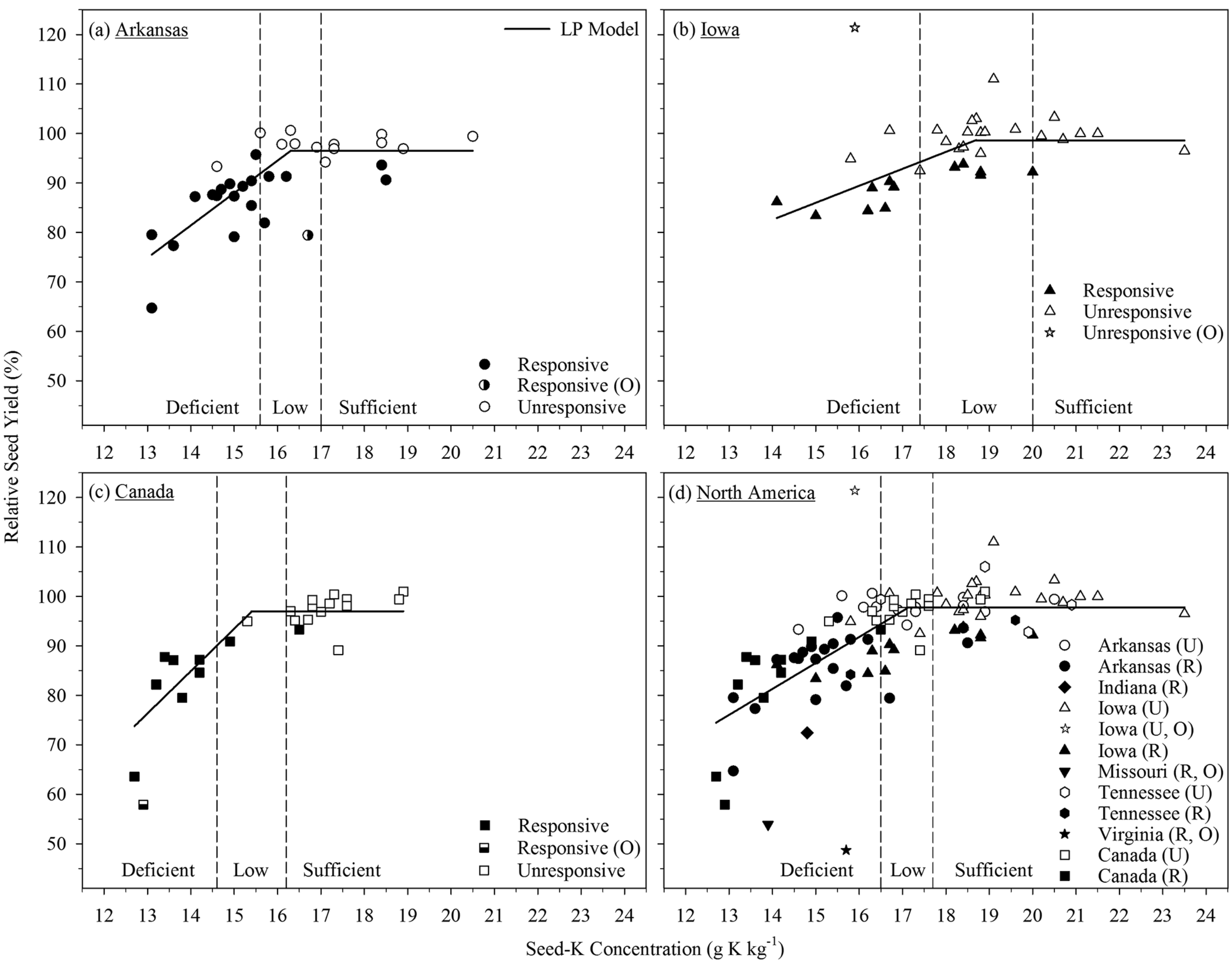

Fig. 1. Relationship between relative soybean yield and seed-K concentration as predicted with linear-plateau (LP) model across (a) 33 sites (Sites 1–33) in Arkansas; (b) 34 sites (Sites 34–67) in Iowa; (c) 24 sites (Sites 68–91) in Ontario, Canada; and (d) 100 sites (Sites 1–100) in North America. Responsive (R) or unresponsive (U) indicates whether or not soybean seed yield was significantly increased by fertilizer K at the 0.10 probability level for Sites 1 to 67 and at the 0.05 probability level for Site 68 to 100 and is shown in Table 2. Site 4 [Responsive (O)] for Arkansas, 65 [Unresponsive (O)] for Iowa, 91 [Responsive (O)] for Canada, and 65 [Iowa (U, O)], 99 [Missouri (R, O)], and 100 [Virginia (R, O)] for North America were identified as outliers and omitted from the statistical analysis. The two vertical dashed lines indicate the critical or low seed-K concentration thresholds. The LP model coefficients and the low seed-K concentration thresholds for each geographic location are listed in Table 3.

to that observed for Arkansas and slightly better than defined for the Iowa sites (Table 4). The frequency and magnitude of yield benefit from fertilizer K declined as seed-K concentrations moved from deficient to low to sufficient. The dataset from Canada contained only two sites within the critical range, of which one site responded to fertilizer K. Despite the lack of sites within the critical range, all sites classified as deficient benefitted from fertilizer K, and only 1 of 14 sites within the sufficient seed-K level responded positively to fertilizer K.

North America

The relative yield of soybean receiving no fertilizer K ranged from 48.7 to 121.4% and seed-K concentrations were 12.7 to 23.5 g K kg^{-1} (Table 2; Fig. 1d). Averaged across all 100 sites in North America, soybean receiving no fertilizer K produced a mean yield of 3373 kg ha^{-1}, compared with 3643 kg ha^{-1} when fertilizer K was applied. The LP model showed a significant relationship between relative soybean yield and seed-K concentration when all sites were considered and showed that seed K plateaued at 17.1 g K kg^{-1}, had a 95% CL of 16.3 to 17.9 g K kg^{-1}, and explained 46% of the relative yield variability. However, three sites—one in Iowa (Site 65), one in Missouri (Site 99), and one in Virginia (Site 100)—were identified as outliers and omitted from the dataset, and the model was refit. Soybean seed-K concentration accounted for 60% of the variability in relative yield (Table 3; Fig. 1d). The revised model predicted the critical seed-K concentration as 17.1 g K kg^{-1} with a 95% CL of 16.5 to 17.7 g K kg^{-1}.

The deficient seed-K level was reasonably accurate at identifying K responsive sites, with 77% of the sites showing a significant yield benefit to fertilizer K that averaged 485 kg ha^{-1} (Table 4). Soybean having low or sufficient seed-K concentrations responded positively to fertilizer K at 23 or 24% of the sites within each category. Although a similar percentage of sites classified as low and

Table 3. Relationship between soybean seed-K concentration (SKC) and relative seed yield (RSY) as predicted with the linear–plateau (LP) model.

Model†	Coefficients		R^2	Join point		95% confidence limits (CL)‡	
	Intercept	Slope		SKC	RSY	Lower CL	Upper CL
				g K kg^{-1}	%	g K kg^{-1}	
Arkansas							
LP	−10.3	6.552	0.66	16.3	96.5	15.6	17.0
SE	17.6	1.172	–	0.4	4.6	–	–
Iowa							
LP	34.6	3.427	0.48	18.7	98.6	17.4	20.0
SE	15.0	0.874	–	0.6	4.5	–	–
Canada							
LP	−35.0	8.565	0.78	15.4	97.0	14.6	16.2
SE	25.8	1.849	–	0.4	4.1	–	–
North America							
LP	7.8	5.250	0.60	17.1	97.7	16.5	17.7
SE	9.6	0.625	–	0.3	5.6	–	–

† Each model [RSY = intercept + (slope × SKC)] was significant at the 0.0001 probability level.

‡ Seed-K concentration (SKC) thresholds for the deficient, low (e.g., critical range), and sufficient seed-K levels were calculated using the 95% CL of the LP model join point. Seed-K concentrations below the lower CL threshold were considered deficient and concentrations greater than the upper CL threshold were considered sufficient. Seed-K concentrations within the CL were considered low.

sufficient benefitted from fertilizer K, the average yield increase was 5% within the low level and 2% within the sufficient level. The K responsive sites within the sufficient seed-K level originated in Arkansas (2), Tennessee (1), and Iowa (5). The majority of the false-negative errors (positive seed yield response to fertilizer K by soybean having a mean seed-K concentration defined as K sufficient) were from soybean grown in Iowa, which suggests that geographic-specific interpretation of seed-K concentrations may be needed for some soybean-producing regions. The seed-K concentrations of the five Iowa sites showing false-negative errors were classified as low for the Iowa-specific interpretation (Table 4). The two Arkansas sites were false-negative errors within the Arkansas-specific and North America interpretations. The one site from Tennessee showing a false-negative error for the North America dataset interpretation would have been within the sufficient seed-K level for the Arkansas and Canada interpretations and within the critical range for the Iowa interpretation (Table 3). Specific reasons why the interpretation of Iowa seed-K concentrations tended to be different are unknown but could be related to the fact that the absolute yield increases attributed to fertilizer K tended to be smaller than for Canada and Arkansas (Table 4).

The deficient seed-K level was reasonably accurate for predicting whether soybean responded positively to fertilizer K with false-positive errors occurring at 23% of the sites (Table 4) with no consistent error associated with seed-K concentrations from a specific region (two in Arkansas, zero in Canada, five in Iowa, and one in Tennessee). With the exception of Iowa-specific guidelines, the deficient seed-K levels for Arkansas, Canada, and North America were quite accurate at identifying when soybean yield would be significantly increased by fertilizer K. Because a number of factors can influence crop yield, information used to diagnose plant nutritional maladies are not required to be perfect. However, the diagnostic information should have a high rate of success at correctly identifying nutrient sufficiency, deficiency, or both.

The overall average seed-K increase from fertilizer K was 1.9 g K kg^{-1} for the deficient category (<16.5 g K kg^{-1} as defined by the seed-K concentration of soybean receiving no fertilizer K) and 0.8 g K kg^{-1} for seed in the critical and sufficient categories. Although seed-K concentration was sometimes increased by up to 6.0 g K kg^{-1}, the average increase from fertilization was not great enough to elevate seed-K concentrations above the defi-

Table 4. The frequency of yield increase to K fertilization, mean relative yield of soybean receiving no fertilizer K, and the average yield increase to fertilizer K across 33 sites in Arkansas, 34 sites in Iowa, 24 sites in Canada, and 100 sites in North America for deficient, low, and sufficient seed-K concentrations levels.

Location†	Frequency of yield increase			Mean relative yield			Yield increase‡		
	Deficient	Low	Sufficient	Deficient	Low	Sufficient	Deficient	Low	Sufficient
	% of sites			% of maximum yield			kg ha^{-1}		
Arkansas	93	44	22	86	93	96	614	265	150
Iowa	70	28	0	92	98	100	263	63	0
Canada	100	50	7	79	93	97	491	185	94
North America	77	24	23	86	95	98	485	172	59

† The low seed-K concentration thresholds as defined by regression analyses was 15.6–17.0 g K kg^{-1} for Arkansas, 17.4–20.0 g K kg^{-1} for Iowa, 14.6–16.2 g K kg^{-1} for Canada, and 16.5–17.7 g K kg^{-1} for North America (Table 3).

‡ Yield increase is the average difference between soybean that received fertilizer K and soybean that received no fertilizer K for all sites (responsive and unresponsive) within each seed-K concentration level (deficient, low, and sufficient) of each geographic location.

cient ($\geq$16.5 g K kg^{-1}) threshold in 16 of the 44 site-years identified as deficient (Table 3). Thus, identification of possible K deficiency using seed-K concentrations must be done with caution and perhaps interpreted along with field-specific information such as soil-test K concentration, fertilizer-K rate applied, and factors that influence K uptake by plants.

The ability to confidently identify what is not a problem can be equally as important as identifying the specific problem. Although specific reasons for the false-positive and false-negative errors are not evident, the errors could be associated with analytical errors or seed subsampling errors. Parvej et al. (2016) reported that seed-K concentrations declined from the bottom to the top of the plant with the greatest differences occurring when K was yield limiting. Soybean cultivars of different maturity groups with different genetic backgrounds are grown among the geographic locations represented in this dataset. Genetics, environment, or production practices could all be sources contributing to the differences in seed-K thresholds among geographic regions (Sale and Campbell, 1987). Although the diversity represented in the 100 sites in North America may contribute to the false-positive and false-negative errors, the robust database makes the information more applicable across a wide geographic area.

Soybean seed nutrient concentrations have been used to diagnose S, Mn, Zn, B, Cu, and Mo deficiencies (Cox, 1968; Hitsuda et al., 2004, 2010; Lavy and Barber, 1963; Parker et al., 1981; Reinbott et al., 1997; Wiersma, 2005). However, there was no literature describing the relationship between seed yield and seed-K concentration for soybean or other crops. Mallarino and Higashi (2009) attempted to diagnose K deficiency of corn using mature seed- and stalk-K concentrations but reported no significant correlation between relative corn yield and seed- or stalk-K concentrations. Clover and Mallarino (2013) noted that grain-K concentration in corn was less frequently affected by fertilizer K than the seed-K concentration of soybean.

Relationships between Seed and Soil Potassium Concentrations

Several researchers have suggested that when soybean seed-K concentrations are increased by fertilizer K, yield increases from fertilization are likely to occur (Clover and Mallarino, 2013; Slaton et al., 2013). The data assembled to examine seed K as a postharvest means of diagnosing K deficiency allow us to evaluate how seed-K concentration is affected by soil- and fertilizer-K availability. For the North America sites, the relationship between seed-K and soil-test K concentrations was determined in two separate evaluations using either the seed-K concentration of soybean receiving no fertilizer K (Fig. 2a) or soybean fertilized with K (Fig. 2b). The seed-K concentration of soybean receiving no fertilizer K increased linearly as soil-test K concentration increased to 179 mg K kg^{-1} and seed-K concentration plateaued at 18.8 g K kg^{-1} (Fig. 2a). Soil-test K concentration explained 40% of the variability in seed K. For soybean receiving fertilizer K, seed-K concentration increased linearly until soil-test K concentration reached 170 mg K kg^{-1}, at which point seed K plateaued at 19.1 g K kg^{-1} (Fig. 2b). Soil-test K concentration explained only 24% of the seed-K variability when fertilizer K was applied. The lower R^2 value for soybean receiving fertilizer K was expected because some proportion of the plants' K needs was supplied by a source other than the soil K. The relationships, as defined by quadratic or LP models, for Arkansas-, Iowa-, and Canada-specific datasets showed that the slope coefficients were not different from zero or that the entire model was not significant

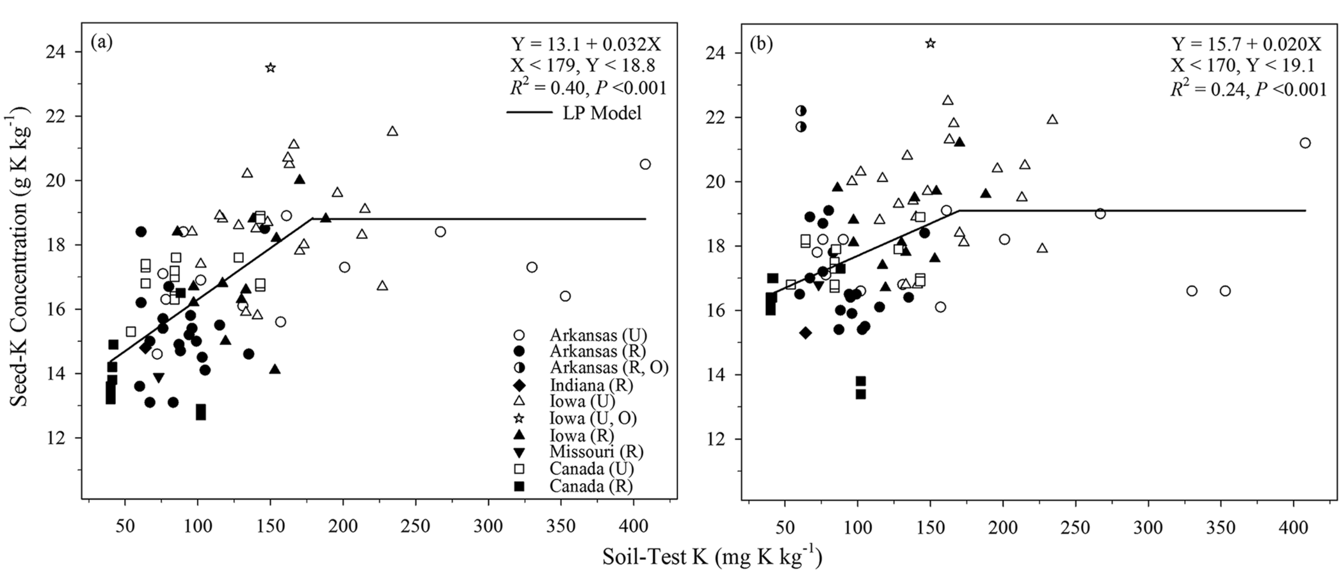

Fig. 2. Relationships between seed-K concentrations of (a) soybean receiving no K fertilizer and (b) K-fertilized soybean and soil-test K concentrations as predicted with a linear-plateau (LP) model across 93 sites (Sites 1–91 and 98–99) in North America. Responsive (R) or unresponsive (U) indicates whether or not soybean seed yield was significantly increased by fertilizer K at the 0.10 probability level for Sites 1 to 67 and 0.05 probability level for Sites 68 to 100 and are shown in Table 2. Sites 2 and 3 [Arkansas (R, O)] for only K-fertilized soybean and Site 44 [Iowa (U, O)] for both no–K-fertilized and K-fertilized soybean were identified as outliers and omitted from the statistical analysis. The soil K was extracted by Mehlich-3 for Sites 1 to 33, 90 to 91, and 99 by NH_4OAc for Sites 34 to 89 and 98 and by Mehlich-1 for Sites 92 to 97 and 100 (Table 2). Sites located in Tennessee (Sites 92–97) and Virginia (Site 100) used Mehlich-1 and were omitted from the regression.

for soybean receiving or not receiving fertilizer K (not shown). Simple linear relationships for Arkansas, Iowa, or Canada were either not significant ($P > 0.05$) or had low coefficients of determination ($R^2 < 0.11$; not shown). The only literature we could find on this subject stated there was no significant relationship between corn seed-K and soil-test K concentrations (Mallarino and Higashi, 2009).

The relationships between seed-K and soil-test K concentrations suggested that fertilizer- and soil-K availability both influence soybean seed-K concentration when soil-test K concentration is <170 to 179 mg K kg^{-1}. To better explain how soil and fertilizer K interact, the seed-K difference (with fertilizer K, – no fertilizer K) was calculated and regressed against soil-test K concentration (Table 5; Fig. 3). The relationship was significant for each of the four geographic locations (Table 5) and showed that the difference in seed-K concentration decreased as soil-test K concentration increased, with seed-K difference plateauing when soil-test K concentration was ≥87 mg K kg^{-1} for Arkansas (Fig.

Table 5. Relationship between soybean seed-K concentration difference (SKCD, seed K with fertilizer K minus seed K without fertilizer K) and soil-test K concentration (STKC) as predicted with a linear–plateau (LP) model.

Model†	Coefficients		R^2	Join point‡	
	Intercept	Slope		STKC	SKCD
				mg K kg^{-1}	g K kg^{-1}
Arkansas					
LP	12.7	−0.138	0.72	87	0.63
SE	2.5	0.035	–	5	0.80
Iowa					
LP	4.0	−0.022	0.37	139	0.89
SE	0.9	0.007	–	11	0.47
Canada					
LP	5.6	−0.073	0.94	73	0.32
SE	0.4	0.009	–	3	0.28
North America					
LP	3.9	−0.029	0.37	104	0.82
SE	0.5	0.006	–	8	0.80

† Each model [SKCD = intercept + (slope × STKC)] was significant at the 0.0001 probability level.

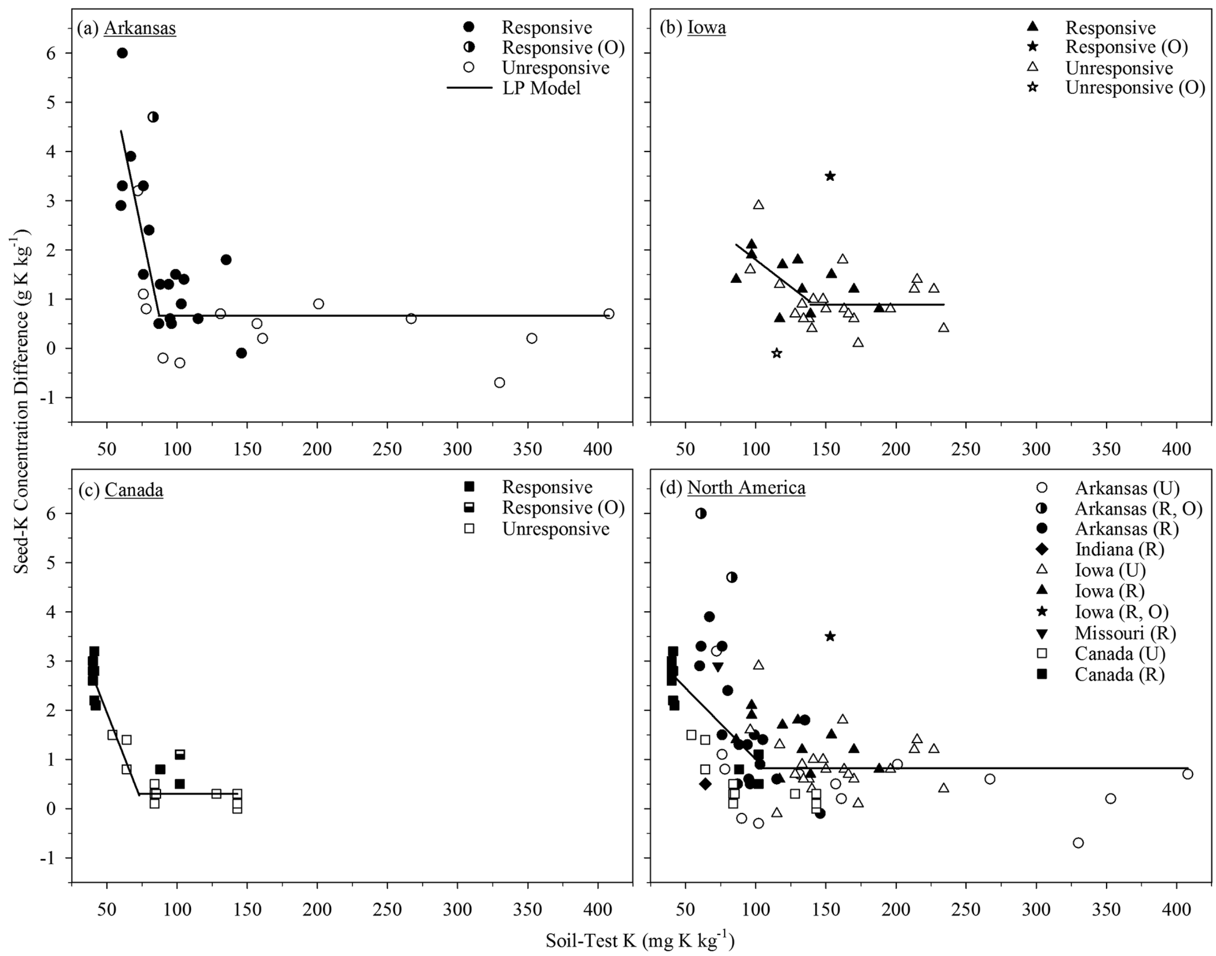

Fig. 3. Relationships between soybean seed-K concentration difference (seed K with fertilizer K minus seed K without fertilizer K) and soil-test K concentration as predicted with a linear-plateau (LP) model across (a) 33 sites (Sites 1–33) in Arkansas; (b) 34 sites (Sites 34–67) in Iowa; (c) 24 sites (Sites 68–91) in Ontario, Canada; and (d) 93 sites (Sites 1–91 and 98–99) in North America. Responsive (R) or unresponsive (U) indicates whether or not soybean seed yield was significantly increased by fertilizer K at the 0.10 probability level for Sites 1 to 67 and at the 0.05 probability level for Sites 68 to 100 (Table 2). Site 1 [Responsive (O)] for Arkansas, 36 [Responsive (O)] and 63 [Unresponsive (O)] for Iowa, 90 [Responsive (O)] for Canada, and 1 and 2 [Arkansas (R, O)] and 36 [Iowa (R, O)] for North America were identified as outliers and omitted from the statistical analysis. The soil K was extracted by Mehlich-3 for Sites 1 to 33, 90 to 91, and 99 by NH_4OAc for Sites 34 to 89 and 98 and by Mehlich-1 for Sites 92 to 97 and 100 (Table 2). Sites located in Tennessee (Sites 92–97) and Virginia (Site 100) were omitted from the regression for North America. The LP model coefficients for each geographic location are listed in Table 5.

3a), ≥139 mg K kg^{-1} for Iowa (Fig. 3b), ≥73 mg K kg^{-1} for Canada (Fig. 3c), and ≥104 mg K kg^{-1} for North America (Fig. 3d). As with the relationship between seed K and relative yield, the specific reasons for the different critical soil-test K concentration values among geographic locations are not clear. However, the amount of soil K extracted by ammonium acetate and Mehlich-3 is known to be affected by soil drying (Barbagelata and Mallarino, 2013; Martins et al., 2015). Drying soil before extraction can significantly increase the soil-test K concentration. The differences in the amount of K extracted from field-moist and dry soil can be substantial and is well documented for soils from Iowa (Barbagelata and Mallarino, 2013; Luebs et al., 1956) and Arkansas (Martins et al., 2015). This phenomenon may be responsible for many of the false-negative and false-positive yield responses observed, especially for soils that had a relatively high soil-test K concentration.

CONCLUSIONS

The relationship between relative soybean seed yield and seed-K concentration from 100 K fertilization trials conducted across diverse conditions and soybean production systems in North America showed that seed-K concentration can be used to diagnose K deficiency. The results supported our prediction and showed that soybean seed-K concentration explained 48 to 78% of the variability in relative seed yield. The critical seed-K concentrations ranged from 14.6 to 20.0 g K kg^{-1} for specific geographic sites (Arkansas, Iowa, and Canada) and averaged 16.5 to 17.7 g K kg^{-1} when data from all the site-years in North America were considered. Based on the 100 site-years of research, the proposed deficient (<16.5 g K kg^{-1}) seed-K concentration correctly identified fields that responded positively to fertilizer K 77% of the time. Fertilizer- and soil-K availability both influenced soybean seed-K concentration but only when soil-K availability was <170 to 179 mg K kg^{-1}. Although seed analysis is not helpful for identifying and correcting K deficiency during the growing season, as a postharvest tool, seed analysis may be of value for diagnosing potential reasons for lower than expected yields and correcting K deficiency for subsequent crops.

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