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Defining the Potassium Nutritional Requirements and Distribution among Plant Parts of Representative Soybean Cultivars from Different Maturity Groups

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Defining the Potassium Nutritional Requirements and Distribution among Plant Parts of
Representative Soybean Cultivars from Different Maturity Groups

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Crop, Soil, and Environmental Sciences

by

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ABSTRACT

The potassium (K) requirement of soybean [*Glycine max* (L.) Merr.] was investigated to determine whether cultivar sensitivity to K deficiency was affected by growth habit (determinate or indeterminate) and how cultivars from each growth habit accumulate and distribute K among plant structures. We also diagnosed K deficiency across reproductive growth stages (R2-6) using trifoliolate leaf- and petiole-K concentrations and at harvest (R8) using seed-K concentration. Soybean responded similarly to K deficiency in terms of yield, selected yield components, and seed-K concentration, regardless of growth habit. The yield loss from K deficiency was greatest on the middle to upper nodes of the indeterminate cultivar and bottom and upper-middle nodes of the determinate cultivar. Seed-K concentration decreased from the bottom to the top nodes of K-deficient plants compared to K-sufficient plants, suggesting K concentration of seeds collected from the upper nodes would be of value for diagnosing K deficiency. We found that both growth habits accumulated maximal K at the R5.5-6.0 stage with the peak accumulation rate at the R3-4 stage. Soybean accumulated 35-45% of the maximum K by the R2 stage and 65-70% by the R4 stage, suggesting that K deficiency of soybean could possibly be corrected by timely fertilization during the early reproductive stages. Trifoliolate leaf- and petiole-K concentrations from the R2 to R5.5 stages were highly correlated with relative soybean yield. The K concentrations in both tissues peaked near the R2 stage and declined linearly at a constant rate with increasing plant age regardless of cultivar, site-year, and K fertility level, indicating that the critical K concentration at each stage beyond the R2 is a negative linear function of time. Mature seed-K concentration across 100 site-years in North America was strongly correlated with relative soybean yield and may seed analysis be an effective post-season tool for diagnosing K deficiency. The threshold of deficient seed-K concentration ($<16.5 \text{ g K kg}^{-1}$) accurately predicted that soybean yield would be

increased by fertilizer-K at 77% of the sites. These research findings will provide growers with more comprehensive tools to identify fields where K availability to soybean may limit yield.

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DEDICATION

This dissertation is dedicated to my daughter Fatema Parvej, my wife Jesmin Parvej, my parents Rekha Rahman and Atiar Rahman, my sisters Israt Jahan and Ismat Jahan, my parents-in-law Samsun Nahar and Late Abdul Jalil, and my advisor Dr. Nathan Slaton.

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LIST OF ABBREVIATIONS

AcHI, actual harvest index

ApHI, apparent harvest index

AcKHI, actual K harvest index

ApKHI, apparent K harvest index

CL, confidence limits

DAE, days after emergence

L, linear

LP, linear-plateau

MG, maturity group

PTRS, Pine Tree Research Station

RREC, Rice Research and Extension Center

LIST OF PAPERS

CHAPTER 2

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

CHAPTER 3

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CHAPTER 1
Literature Review

Introduction

Fertilization with phosphorus (P) and potassium (K) is often required to produce maximal soybean [*Glycine max* (L.) Merr.] yield and sustain soil fertility and productivity. According to the USDA-ERS (2008), 17 to 21%, 23 to 28% and 23 to 29% of the US soybean hectares receive N, P, and K fertilizers, respectively, since 1997. The fertilizer use statistics also show that fertilization practices vary among soybean-producing states. The costs associated with soybean fertilization in the United States averages around \$58 ha⁻¹, which represents approximately 17% of soybean production expenses (USDA-ERS, 2012a). In Arkansas, the fertilization costs for soybean are estimated to be \$112 ha⁻¹, accounts for 18% of crop production costs, and are primarily for P and K fertilizers (Flanders and Dunn, 2012). Fertilization, therefore, represents a significant portion of soybean production costs and justifies fertilization research that leads to developing nutrient management strategies that enhance nutrient uptake efficiency, increase soybean yield, or both.

Fertilization programs for soybean, as well as other crops, are most commonly based on soil-test results and/or tissue analyses that are conducted during the growing season to monitor the plants nutritional health. The literature contains a wealth of information regarding the interpretation of soil-test results (Grove et al., 1987; Leikam et al., 2010; Slaton et al., 2010, Barbagelata and Mallarino, 2012), soybean trifoliolate leaf analysis (Yin and Vyn, 2004; Slaton et al., 2010; Clover and Mallarino, 2013), and characterizing nutrient uptake patterns during the growing season (Sale and Campbell, 1980; Scott and Brewer, 1980; Batchelor et al., 1984; Flannery, 1986; Sojka et al., 1985, 1989). The most recent description of soybean nutrient uptake patterns was published by Sojka et al. (1985, 1989) and Sadler et al. (1991), which preceded the commercial availability and acceptance of glyphosate-resistant soybean. Soybean production

practices in Arkansas have also changed since the 1980's and early 1990's. Prior to the 1990's, Arkansas farmers almost exclusively planted MG V to VII cultivars having a determinate growth habit. In the past two decades, MG IV cultivars with indeterminate growth habit have increased in popularity and now comprise a significant portion of the hectares (Boquet, 1998).

We are aware of no research that has quantified aboveground nutrient uptake and distribution patterns among plant structures under the same growing conditions, different soil-K availability levels, or among glyphosate-resistant soybean cultivars of different growth habits (e.g., determinate and indeterminate) and maturity groups (especially IV and V). Only limited information is available describing the dry matter accumulation pattern similarities or differences between cultivars with different growth habits (Egli and Leggett, 1973; Beaver et al., 1985; Wilcox and Frankenberger, 1987). The literature contains no information comparing nutrient accumulation patterns and amounts of determinate and indeterminate soybean grown in the same environment. Most of the available information describing the relationship between soybean nutrient concentrations and yield is specific for the most recently mature trifoliolate leaves at the R1-2 growth stage (Grove et al., 1987; Yin and Vyn, 2004; Slaton et al., 2010; Clover and Mallarino, 2013). Sartain et al. (1979) reported a relatively poor correlation between soybean yield and trifoliolate leaf-K concentration at the early bloom stage (R1) compared to the concentration at the early pod stage (R3).

Improved diagnostics for interpreting soybean leaf-K (and other nutrients) concentration across a range of growth stages would enable farmers to confidently assess and manage in-season soybean plant nutrition and could help increase soybean yield and quality. Therefore, the overall goal of the proposed research is to improve our ability to monitor and assess the nutritional status of determinate and indeterminate soybean cultivars by enhancing our

knowledge and understanding of aboveground nutrient uptake and allocation pattern during the growing season. This literature review will summarize information regarding the growth habit, dry matter and nutrient accumulation and distribution pattern, and seed yield of soybean.

Soybean Production in USA and Arkansas

Soybean is grown primarily in the eastern one-half of the United States with the greatest number of hectares located in the Midwest where soybean is the most common crop rotated with grain crops like corn (*Zea mays* L.). Among soybean-producing countries, the United States is ranked first in soybean production. In 2012, in the USA, soybean was grown on about 29.9 million ha, and total production was approximately 84.2 Tg (Tg = 1 million metric tons), which accounted for 29% of the world's soybean production (USDA-FAS, 2013). The average soybean yield, in the United States was 2.82 Mg ha⁻¹, which was greater than the world average yield of 2.12 Mg ha⁻¹ and all individual country yield averages except Italy (3.33 Mg ha⁻¹).

In Arkansas, the soybean-producing areas include the eastern one-half of the state known as the Mississippi Delta Region, the Arkansas River Valley, and the southwestern corner of the state. Arkansas farmers grow a considerable hectareage of determinate and indeterminate soybean cultivars in rotation with rice (*Oryza sativa* L.) or double-cropped following winter wheat (*Triticum aestivum* L.) using either conventional, minimum- or no-tillage practices. Approximately 65 to 75% of Arkansas' soybean hectares is grown under irrigation (USDA-NASS, 2009). According to the USDA-NASS (2012a), Arkansas ranked tenth in total production among soybean-producing states from 2009 to 2011. Arkansas farmers usually plant about 1.34 million ha of soybean annually with an average production of 3.2 Tg yr⁻¹ (3.7% of the total US production). Soybean production in Arkansas has increased by about 2.5% over the last decade from 2.48 Tg in 2001 to 3.38 Tg in 2011 while soybean hectares have increased by only 1.14%

from 1.17 (2001) to 1.37 million ha (2011; USDA-NASS, 2012b). The average soybean yield during this time was 2.42 Mg ha⁻¹ (USDA-NASS, 2012b), which was well below the US average yield of 2.82 Mg ha⁻¹ (USDA-ERS, 2012b). The annual total cost of soybean production in Arkansas is about \$835 ha⁻¹, which includes estimated operating costs of \$702 ha⁻¹ and fixed costs of \$133 ha⁻¹ (Flanders and Dunn, 2012).

Soybean Growth Stages

Soybean development is categorized into two growth phases, the vegetative and reproductive phases. Understanding how soybean grows and develops is important for proper crop management. Kalton et al. (1949) first described the development of soybean with an indeterminate growth habit in the northern states of the USA and divided soybean growth into ten stages. Hanway and Thompson (1967) suggested an almost identical staging system to that proposed by Kalton et al. (1949) for soybean development and divided soybean growth into eleven stages (0-10). The main difference between these two staging systems was that Hanway and Thompson (1967) added one additional growth stage to indicate the time that soybean was mature or ready to harvest.

Fehr et al. (1971) introduced a new soybean growth staging system, which was more rational and acceptable to most scientists and also suitable for genotypes in all environments. They defined vegetative stages on the basis of node number on the main-stem and reproductive stages were related to blooming, pod and seed development, and maturation. The node counting begins with the unifoliolate node, which is the first node on the plant where true leaves develop. The nomenclature identified vegetative growth stages by 'V' and reproductive stages by 'R'. According to Fehr et al. (1971), a soybean plant can start to produce flowers once it has four nodes or may not form flowers and bloom until the plant has as many as 18 main-stem nodes.

Instead of including a complex description of the flowering patterns of indeterminate and determinate soybean, they generalized the reproductive stages by considering the developmental conditions at the upper portion of the main-stem only. The reproductive growth phase starts with the R1 stage when flowers appear on any node of the plant and ends with the R8 stage at maturity.

Soybean cultivars are categorized into several maturity groups ranging from 000 to X based on the duration of the growth cycle. As a general rule, soybean cultivars with a low MG number (shorter growing season) are grown in the northern latitudes and cultivars with an intermediate MG are grown in the southern USA (Zhang et al., 2007). Zhang et al. (2004) showed that the lower the group numbers the shorter the soybean life cycle. For example, soybean cultivars belonging to MG III, IV, and V required an average of 114, 127, and 141 d, respectively, to mature. They found that MG III and IV soybean cultivars bloomed (R1) earlier [33 and 40 d after planting (DAP), respectively] than MG V cultivars (bloomed 49 DAP). The duration of the reproductive growth phase (R1-8) also varied with MG V cultivars having a longer reproductive period (92 d) than MG III (81 d) and IV (87 d) cultivars. Mastrodomenico and Purcell (2012) mentioned that the seed-filling period for MG IV (51 d) soybean was 5 d longer than MG V and VI (46 d) soybean. Egli (1994) and Zhang et al. (2004) both mentioned that the duration of the seed-filling period (R5-7) was not significantly different among the MG III, IV, and V cultivars.

Potassium Function in Soybean Plant Nutrition

Potassium is one of the most important essential nutrients for plant growth and development. Plants require a large amount of K to maintain optimum plant water balance, regulate nutrient uptake, and boost photosynthesis and assimilate partitioning (Pettigrew, 2008). Potassium regulates the rate of photosynthesis by activating over 60 enzymes and assisting in

ATP production (Blevins, 1985) and by regulating stomatal conductance (Huber, 1984).

Potassium-deficit plants exhibit higher transpiration losses due to delayed stomatal resistance and are more subjected to drought stress when a water deficit occurs (Huber, 1984).

Potassium influences the translocation of assimilates from source to sink (Kolar and Grewal, 1994). Sale and Campbell (1986) reported that in K-deficient soybean, the accumulation and translocation rates of assimilate to developing seeds declined during the latter part of seed-filling (R6-7) due to a malfunction in phloem translocation. Jackson and Volk (1968) and Ashley and Goodson (1972) concluded that in K-deficient plants, photosynthates tend to accumulate where they are formed, which decreases the rate of assimilate translocation from source to sink.

Potassium fertilization may influence the uptake of other nutrients including decreasing Ca and Mg uptake (Claassen and Wilcox, 1974; Reneau et al., 1983) and increasing P uptake (Armstrong, 1998). Potassium has been reported to influence soybean yield components in a number of studies under different management and agro-climatic situations. Potassium fertilizer increases the number of pods plant⁻¹ (Bharati et al., 1986; Coale and Grove, 1990), the number of seeds pod⁻¹ (Coale and Grove, 1990), and the weight of individual seeds (Bharati et al., 1986). Potassium fertilization has increased soybean yield by 14 to 83% across soil textures that range from silt loam to clay loams (Bhangoo and Albritton, 1972; Keogh and Maples, 1974; Jones et al., 1977; Grove et al., 1987). In addition to grain yield increases, K fertilization can increase soybean seed quality by increasing oil and isoflavone concentrations by 3 to 16% (Vyn et al., 2002), seed protein content by 11 to 19% (Abbasi et al., 2012), and by reducing pod and stem blight (*Diaporthe sojae* L.) over 90% and purple seed stain (*Cercospora kikuchii* L.) more than 40% (Camper et al., 1978; Snyder and Ashlock, 1996).

Critical Nutrient Concentrations of Soybean

Nutrient concentrations of plant tissues can be categorized into three levels: deficient, critical, and sufficient (Ulrich and Hills, 1967). The critical nutrient concentration is the minimum concentration of a particular nutrient within a specific plant part at which near maximum yield is obtained with no addition of that nutrient (Dow and Roberts, 1982; Mills and Jones, 1996). A critical nutrient concentration can be effectively used to diagnose a nutrient deficiency before and/or after symptoms become visible.

In order to diagnose a plant's nutritional status, the critical nutrient concentration of plant tissue should be considered at a particular growth stage (Harper, 1971). Plant analysis at an early stage does not indicate what the plant nutrient concentration will be during later stages of plant development and the redistribution of nutrients within the plant occurs rapidly during the seed-filling period (Hammond et al., 1951). Leaves or other plant parts may also need to be sampled from a particular position on the plant at a specific growth stage due to the variation in nutrient concentration with the age and position of the plant (Sumner, 1977; Sojka et al., 1989). In order to confirm nutrient deficiency, researchers compare the tissue nutrient concentration with the recommended critical values (Plank, 1979). Therefore, many crop producers effectively use tissue analysis to ensure proper nutrient management for their crops and help ensure that plant nutrition is not yield limiting. The critical and sufficient concentrations of several nutrients in soybean plant tissue are presented in Table 1.1. Tissue nutrient concentration is used to determine whether the present nutrient concentration within the plant is enough to produce maximum yield. Steenbjerg (1951) recognized a relationship between a nutrient concentration in a particular tissue and sufficiency of that nutrient for producing maximum dry matter yield.

Unfortunately, plant samples are not always collected at the specific growth stage for which diagnostic information is available.

The critical K concentration in trifoliolate leaves of soybean has been the focus of research by several scientists (Grove et al., 1987; Yin and Vyn, 2004; Slaton et al., 2010; Clover and Mallarino, 2013). They found that K concentration in the trifoliolate leaves of soybean is highly correlated to seed yield and a crucial component to monitor the in-season nutritional status of soybean. Soybean trifoliolate leaf-K concentration at the R1-2 stage is reported to be a good indicator of the relative yield potential of soybean (Grove et al., 1987; Yin and Vyn, 2004; Slaton et al., 2010, Clover and Mallarino, 2013). Sartain et al. (1979) found that the trifoliolate leaf-K concentration of ‘Bragg’ soybean (MG VII) at the early bloom stage (R1) was a relatively a poor indicator of yield potential. They reported a better correlation between leaf-K concentration at early pod stage (R3) and soybean yield without mentioning any reason. Some researchers have reported a reasonably good correlation between trifoliolate leaf-K concentrations at full-pod stages (R4; Miller et al., 1961) with soybean yield.

The trifoliolate leaf-K concentration at the R1-2 stage reportedly explains from 32 to 82% (i.e., R^2) of the variability in the relative yield of soybean having indeterminate and determinate growth habits and MG ranging from 00 to V (Grove et al., 1987; Yin and Vyn, 2004; Slaton et al., 2010; Clover and Mallarino, 2013). According to Slaton et al. (2010), trifoliolate leaf-K concentrations ≥ 19 g K kg⁻¹ are considered sufficient for determinate soybean. Using a linear-plateau model, they reported that a predicted relative yield of 85% was associated with a leaf-K concentration of 15 g K kg⁻¹ and the maximum predicted relative yield of 96% was produced by plants having 18.8 g K kg⁻¹. Similar interpretations of trifoliolate leaf-K concentration were reported by Hanway and Johnson (1985), Grove et al. (1987), and Clover and

Mallarino (2013). Yin and Vyn (2004) documented that maximum seed yield, seed oil, and isoflavone concentration of soybean grown in a conservation-tillage system was achieved when the trifoliolate leaf-K concentration was 24.6 to 25.9 g K kg⁻¹ at the R1 growth stage.

Potassium Deficiency of Soybean

Potassium is mobile in plants and readily translocated from the older plant parts to the younger parts throughout the growing season. That is why K deficiency is normally expressed in the older leaves of soybean plants (Snyder and Ashlock, 1996). Sinclair (1993) described K deficiency as an irregular yellowing (chlorosis) along the margin of the older leaves. As the severity of K deficiency increases, the leaf edges become necrotic and the chlorosis/necrosis progresses towards the leaf margin (Varco, 1999). Similar symptoms associated with K deficiency have been described by Jeffers et al. (1982) and Sale and Campbell (1986) on the upper, younger leaves rather than lower, older leaves during mid-to late-season (seed-filling period; R5-7). Snyder and Ashlock (1996) declared that field-grown soybean in eastern Arkansas show K deficiency symptoms during late-season in the middle to upper canopy on soils testing <50 mg K kg⁻¹. They also reported that K deficiency can be severe in the upper canopy due to rapid seed development compared to the lower canopy with limited seed development.

In semi-determinate and/or indeterminate cultivars, Snyder and Ashlock (1996) reported that K deficiency symptoms appeared in the upper leaves instead of the lower leaves due to simultaneous vegetative and reproductive growth which may affect K partitioning in K-deficient soybean plants. Similar K deficiency symptoms have also been observed by other researchers (Ohlrogge, 1960; Jeffers et al., 1982), who explained that the rate of translocation of K from the lower, older leaves to the upper leaves may not be sufficiently rapid to meet the high K demand during the seed-filling period. Hanway and Weber (1971b) showed that later in the growing

season, trifoliolate leaf-K concentrations of indeterminate soybean declined more in the top portion of the plant than in the middle and lower plant portion, which coincides with the growth period with the greatest demand for K. A similar observation was made by Drossopoulos et al. (1994) who noted that K remobilizes mainly from the middle and upper leaves rather than the lower leaves to the reproductive sinks. Overall, the more likely explanation for K deficiency symptoms appearing in the upper leaves is that during the seed-filling period, developing pods and seeds become the dominant sink for K and probably contribute to the less-than-optimum supply of K to the upper leaves (Hanway and Johnson, 1985), thus resulting in the expression of K deficiency in the upper leaves when the soil K supply is inadequate to satisfy plant K needs.

Characterization of Soybean Growth Habit and Dry Matter Accumulation

Soybean cultivars grown in the United States exhibit either a determinate or indeterminate growth habit. Cultivars with a determinate growth habit have typically been grown in the southern United States, whereas indeterminate soybean cultivars have been grown in the northern United States (Johnson and Bernard, 1962). Determinate cultivars are usually found from MG V to X and indeterminate cultivars include MG 000 to IV, but there are some exceptions (Ashlock and Purcell, 2000). In Arkansas, farmers most commonly plant either MG IV cultivars that have an indeterminate growth habit or MG V cultivars that exhibit determinate growth. According to Pedersen et al. (2004), indeterminate and determinate genotypes grow in a similar fashion early in the growing season, but their growth changes dramatically after flower initiation (R1). The basic difference between the two growth habits is that determinate plants cease main-stem vegetative growth at or soon after the onset of reproductive growth (flowering) while indeterminate plants continue vegetative growth for several weeks (as long as 40 d) after flower initiation (Bernard, 1972; Pedersen et al., 2004). Compared with indeterminate soybean

cultivars, determinate cultivars are generally shorter, have fewer main-stem nodes, more lateral branches, and are less susceptible to lodging (Hicks et al., 1969; Egli and Leggett, 1973; Beaver et al., 1985; Cooper, 1985; Foley et al., 1986; Wilcox and Frankenberger, 1987; Ouattara and Weaver, 1994).

The duration of reproductive growth stages varies between determinate and indeterminate soybean. Egli and Leggett (1973) found that an indeterminate, MG IV cultivar flowered (R1) 14 d earlier than a determinate cultivar with a similar maturity. Determinate cultivars flower (R1-2) within a short period compared to indeterminate cultivars (Hicks et al., 1969; Terman, 1977). Wilcox and Frankenberger (1987) found that the flowering (R1-2) period in MG III indeterminate cultivars lasted 3-5 d longer than MG III determinate cultivars grown in the same environment. Egli and Leggett (1973) reported that the flowering to pod set (R1-4) period in an indeterminate cultivar was 6 to 8 d longer than a determinate cultivar. Beaver and Cooper (1982) explained that the earlier flowering of indeterminate soybean might lengthen the pod set period without affecting the time of maturation.

According to Wilcox and Frankenberger (1987), the total seed-filling period (R5-7) in determinate soybean was 3-4 d longer than for indeterminate soybean, although the R5-6 stage was essentially the same for both genotypes. They also reported a similar duration of the entire reproductive phase (R1-8) for both growth habits which amounted to 67-74 d depending upon the time of planting and location. This result indicates that indeterminate cultivars adjusted the duration of the reproductive phase by lengthening the flowering and pod set period (R1-4) and the determinate cultivars adjusted its seed development period (R5-7). As a general rule, the duration of reproductive growth of indeterminate soybean cultivars is at least 2-3 d or more than that of determinate soybean with similar maturity (Beaver et al., 1985; Ouattara and Weaver,

1994). The slightly longer reproductive phase in indeterminate soybean does not impart a consistent and significant seed yield advantage (Beaver et al., 1985; Ouattara and Weaver, 1994).

The dry matter accumulation of field-grown soybean has been studied by many researchers (Hanway and Weber, 1971a, d; Egli and Leggett, 1973; Kollman et al., 1974; Beaver et al., 1985). According to Egli and Leggett (1973) and Beaver et al. (1985) determinate and indeterminate genotypes accumulate dry matter in a similar pattern across time during the vegetative and reproductive growth phases. Both genotypes differ in the dry weight of different plant parts at various stages of plant growth, but the total amount of dry matter at maturity is comparable. Beaver et al. (1985) found that determinate soybean cultivars accumulate less dry matter in the main-stem, but partially compensate by accumulating more dry matter in branches than indeterminate cultivars. Egli and Leggett (1973) and Beaver et al. (1985) both illustrated that, regardless of plant growth habit, the dry matter accumulation of reproductive plant structures (e.g., flowers, pods, and seeds) was linear. A determinate cultivar had a greater number of pods and total seed weight on branches, but produced fewer main-stem nodes than the indeterminate cultivar (Beaver et al., 1985).

Egli and Leggett (1973) determined that a MG III determinate strain reached 84% of its maximum height and had produced 67% of its stem dry weight at initial flowering, as compared to 64% of maximum height and 30% of maximum stem dry weight for a MG III indeterminate cultivar. The determinate cultivar had produced 11 of its 12 total main-stem nodes by initial flowering whereas the indeterminate cultivar had produced only 9 of its 16 total main-stem nodes by flowering. Beaver et al. (1985) reported that soybean of both growth habits accumulated maximum leaf dry matter 77 (indeterminate) to 84 (determinate) days after emergence (DAE) and maximum petiole dry weight at 84 (indeterminate) to 91 (determinate) DAE. Egli and

Leggett (1973) summarized that the determinate cultivar produced 78% of its total vegetative dry matter by initial flowering (R1) compared to 58% for the indeterminate cultivar. Upon the initiation of pod development (R4-5), both genotypes had accumulated an average of 87% to 92% of their total aboveground, vegetative dry matter. At the time (R5-6; 89 DAP) of maximum dry weight accumulation of the vegetative structures, the stems, leaves, and petioles accounted for an average of 44, 40, and 16%, respectively, of the total vegetative dry matter in both determinate and indeterminate soybean. They concluded that compared to a determinate cultivar, the indeterminate cultivar accumulated more dry weight from the flowering (R1) to pod set (R4) period due to its simultaneous vegetative and reproductive growth and longer flowering and pod set period. The distribution of dry matter also varies among the nodes of soybean plants. Sojka et al. (1983) and Sadler et al. (1991) reported that a MG VII, determinate soybean at the R7 stage produced the greatest leaf area from the middle nodes (7-12th nodes of 20-21 total nodes) with the single greatest dry matter (e.g., main-stem, leaves, branch, petioles, pods and seeds associated with each node) produced at node 8.

Scientists have postulated that the simultaneous vegetative and reproductive growth of indeterminate soybean may be detrimental to pod set and grain yield due to competition for assimilates between vegetative and reproductive sinks (Hicks and Pendleton, 1969; Egli and Leggett, 1973; Tanner and Ahmed, 1974). The competition for assimilates in indeterminate soybean may reduce the proportion of assimilate partitioned to reproductive sinks and result in decreased grain yield (Tanner and Ahmed, 1974). Dunphy et al. (1979) reported that the flowering period (R1-2) of 119 cultivars (probably indeterminate soybean cultivars from MG I and II) in Iowa was weakly correlated ($R = 0.20$) with soybean yield and the length of the pod development period (R2-4) was negatively correlated ($R = -0.26$) with yield. However, the

duration of the seed-filling period (R4-7) was highly correlated ($R = 0.51$) with soybean seed yield. A similar relationship between seed-filling period and seed yield was reported by Hanway and Weber (1971d) and Egli and Leggett (1973). Egli and Leggett (1973) argued that indeterminate cultivars may compensate for yield loss from assimilate competition between the vegetative and reproductive sinks by producing more assimilate during their longer flowering and pod set period (R1-4). For this reason, Bernard and Weiss (1973) suggested that cultivars possessing the indeterminate growth habit could have a yield advantage over determinate cultivars in low yield environments. Numerous researchers have proposed that there is no consistent yield advantage between determinate and indeterminate soybean (Egli and Leggett, 1973; Beaver and Johnson, 1981; Beaver et al., 1985).

Soybean Nutrient Uptake and Partitioning

Nutrient uptake in soybean is more or less parallel to dry matter accumulation and both parameters peak at nearly the same time (Henderson and Kamprath, 1970; Hanway and Weber, 1971c). However, the rate of nutrient uptake and composition by soybean varies among nutrients (Scott and Brewer, 1980), plant parts (Henderson and Kamprath, 1970), nodal positions (Sadler et al., 1991), plant growth stages (Scott and Brewer, 1980; Batchelor et al., 1984), and growing seasons (Scott and Brewer, 1980). Latitude, soil texture, soil fertility, cultivar, and environmental conditions also influence the nutritional status of soybean plant structures (Ohlrogge, 1960; Leggett and Egli, 1980).

Soybean generally accumulates N, P, and K at a low rate early in the growing season, but the accumulation rate increases sharply and peaks during the late vegetative stage to pod development stage and then declines until maturity (Henderson and Kamprath, 1970; Harper, 1971; Hanway and Weber, 1971c; Sadler et al., 1991). The accumulation of these nutrients

occurs in the vegetative structures including leaves, petioles, and stems until the beginning of the seed-filling period (R5), and in the reproductive structures from the early pod development stage (R3) to physiological maturity stage (R7) specifically in pods from R3 to R5, and in seeds from R5 to R7 (Hanway and Weber, 1971c). The accumulation rates of nutrients vary between the vegetative and the reproductive structures of both determinate and indeterminate soybean. Regardless of growth habit, the vegetative structures accumulate N, P, and K at a slower rate compared to the reproductive structures (Hammond et al., 1951; Scott and Brewer, 1980).

The rates of nutrient accumulation by soybean with determinate and indeterminate growth habits may differ among nutrients and plant growth stages. Irrespective of soybean growth habit, the maximum demand of N and P for the aboveground plant parts occurs during the early- to-mid seed-filling period (R5-6) and maximal demand for K occurs from immediately after full-bloom to pod development (R2-4; Henderson and Kamprath, 1970; Flannery, 1986). Sadler et al. (1991) determined the maximum accumulation rates of 4.4 kg N and 0.6 kg P ha⁻¹ d⁻¹ at 100 DAP (R5-6) and 4.1 kg K ha⁻¹ d⁻¹ at 70 DAP (R2-3) for a determinate soybean (MG VII; 149 d maturity period). Flannery (1986) reported that the maximum accumulation rates of N, P, and K in the aboveground plant parts of an indeterminate soybean were 11.4 kg N and 1.2 kg P ha⁻¹ d⁻¹ at 103 DAE (R5-6) and 8.0 kg K ha⁻¹ d⁻¹ at 82 DAE (R3-4) in research investigating nutrient uptake in a very high yield environment (125-130 d cultivar that produced 6.8 Mg ha⁻¹). Henderson and Kamprath (1970) worked with a determinate MG VI cultivar and Hanway and Weber (1971c) worked with an indeterminate MG II cultivar and reported comparable average N, P, and K accumulation rates during the flowering (R2) to seed-filling period (R6), which ranged from 3.6 (determinate) to 4.5 (indeterminate) kg N, 0.3 to 0.4 kg P, and 1.8 to 1.5 kg K ha⁻¹ d⁻¹. According to Sale and Campbell (1980) and Sadler et al. (1991), nutrient accumulation

in soybean seeds, regardless of growth habit, occurs at a faster rate during the early seed-filling period (R5) compared to the late seed-filling period (R6-7) and seeds reach maximum nutrient content at maturity (R8).

The nutrient composition of soybean tissue varies among nutrients, growth stages, and nodal positions. Sadler et al. (1991) revealed that determinate soybean accumulated 20 to 25% of its maximum N, P, and K content by full-bloom (R2), 47 to 71% by pod development (R3-4), and N, P, and K accumulation was complete (100%) by the seed-filling stage (R6). Flannery (1986) reported that the N, P, and K accumulation by an indeterminate soybean cultivar was 30 to 35% of maximum by R2, 56 to 68% of maximum by R3-4, and maximum by the R6 stage. Sadler et al. (1991) showed that N, P, and K accumulation fluctuated among the nodes of MG VII determinate soybean plants. Approximately 50% of the maximum N, P, and K content came from the middle nodes (7-12th nodes of 20 total nodes) 127 DAP at the R6 stage (149 d cultivar).

The maximum aboveground nutrient content of soybean, regardless of MG or growth habit, usually occurs at the R6 to R7 stage and ranges from 242 to 614 kg N ha⁻¹, 21 to 65 kg P ha⁻¹, and 150 to 403 kg K ha⁻¹ for soybean that produced seed yields of 3.7 to 6.8 Mg ha⁻¹ (Henderson and Kamprath, 1970; Flannery, 1986; Sadler et al., 1991). The peak accumulation period of N, P, and K for soybean, regardless of growth habit, coincides with the seed-filling period (R5-7) when the plant demand for nutrients reaches a peak (Hammond et al., 1951; Sadler et al., 1991). Henderson and Kamprath (1970) concluded that K accumulation in the aboveground portion of a determinate soybean cultivar was greater than the total decrease that occurred in the vegetative plant parts, suggesting continuous uptake of K by plant roots for a short period after leaf senescence.

Hanway and Weber (1971b; indeterminate cultivars) and Sojka et al. (1985, 1989; determinate cultivar) determined that the percent N, P, and K in the vegetative structures including leaves, petioles, and stems of soybean generally increases during the early vegetative growth phase and thereafter gradually decreases with plant age. Early in the growing season, the N and P concentrations in leaves were much higher than in the petioles and stems, but the opposite was observed for K. By the end of the growing season, all nutrient concentrations become low in the vegetative plant parts. In contrast, the concentrations of nutrients in reproductive structures (e.g., pods and seeds) increase as the plant proceeds towards maturity. In pods, the nutrient concentration increases initially and thereafter decreases due to the mobilization of nutrients from pods to seeds. The reported maximum N, P, and K concentration in the aboveground plant parts of soybean is presented in Table 1.2.

The N, P, and K concentration in different plant parts also varies among the main-stem nodes for both determinate (Sojka et al., 1985, 1989) and indeterminate (Hanway and Weber, 1971b) soybean across the growing season. Research suggests that the concentration of N tends to be greater towards the top of the plants, the P concentration remains relatively constant from top to bottom, and the K concentration varies within the plant parts of each node or group of nodes. In general, the mean concentration of K increases up to 6-8th nodes at maturity and then decreases gradually towards the top of the soybean plants. Although the N, P, and K accumulation increases in the aboveground plant structures across the growing season, the concentration of these nutrients decreases in each plant part other than the seeds towards maturity due to dilution (Henderson and Kamprath, 1970; Hanway and Weber, 1971b; Harper, 1971; Sale and Campbell, 1980; Sojka et al., 1985, 1989).

Hammond et al. (1951, indeterminate cultivar) and Sadler et al. (1991, determinate cultivar) both reported that the vegetative structures of soybean contained, the 40 to 50% of the total plant N, P, and K content at the time of maximum nutrient accumulation (R6 stage) compared to 15 (N, P) to 30% (K) of the plant's total nutrient content at maturity (R8). Furthermore, at maturity, the pods and seeds of a determinate cultivar contained 90% of the N, 83% of the P, and 66% of the K and the seeds of an indeterminate cultivar contained 80% of the N, 83% of P, and 72% of the K. This result indicates that a significant amount of these nutrients was mobilized from the vegetative to the reproductive plant structures (seeds) during the seed-filling period. In general, the apparent nutrient harvest index (mature seeds nutrient content ÷ aboveground mature plants nutrient content; Schapaugh and Wilcox, 1980) of soybean ranges from 0.80 to 0.89 for N, 0.83 to 0.91 for P, and 0.70 to 0.72 for K (Hammond et al., 1951; Hanway and Weber, 1971c; Crafts-Brandner, 1992).

The vegetative structures of soybean plants (e.g., leaves, petioles, stems, and branches) store mineral nutrients during the growing season. Pods, a reproductive structure, also serve as a reservoir of nutrients for developing seeds. The depletion of nutrients stored in these plant parts during the seed-filling period has been attributed to the mobilization and subsequent translocation into the developing seeds (Scott and Brewer, 1982). Sale and Campbell (1980) showed that about 80% of the total N, P, and K content of the seeds was translocated by the onset of leaf senescence (R7), but each of the nutrients followed a slightly different pattern of translocation. According to Hanway and Weber (1971c), soybean seeds accumulate N, P, and K from two pathways including active nutrient uptake by the roots and translocation of nutrients from other plant parts. They reported that the mobilization of nutrients stored in the plant contributes more than 50% of the nutrients accumulated in mature soybean seeds highlighting the

important function of vegetative organs as sources of N, P, and K for the developing seeds. They also indicated that soybean leaves are more important than stems as a source of mobilized nutrients, especially N, P, and K. Overall, the percentage of N, P, and K translocation from the vegetative to reproductive structures in soybean is in the order of $P > N > K$ (Scott and Brewer, 1980).

In soybean production, N serves as an important yield-determining factor. Soybean seeds demand a high amount of N compared to other elements and the N demand cannot be satisfied by the daily N uptake rates resulting in the mobilization of N from the vegetative plant tissues (Sinclair and de Witt, 1976; Vasilas et al., 1995). Hammond et al. (1951) showed that the total-N content of the plant increased about 54 kg N ha^{-1} from 87 to 138 (maturity) DAP whereas the total-N content of the seeds and pods increased around 136 kg ha^{-1} during the same period. The 82 kg N ha^{-1} difference in total aboveground-N content and seed-N accumulation suggests that N is efficiently translocated from the vegetative plant structures to the soybean seeds (Vasilas et al., 1995). Hanway and Weber (1971c) reported that about 68% of the total-N was translocated to the seeds. Vasilas et al. (1995) found that soybean translocates 66 to 79% of its vegetative N content to the developing seeds. Zeiher et al. (1982) concluded that the N mobilized from the aboveground plant parts of soybean to the seeds was 53% from the leaves, 21% from the pods, 21% from the stems, and 4% from the petioles. In summary, the literature suggests that soybean plants mobilize and translocate at least 50% and as much as 80% of the N stored in its vegetative structures to the developing seeds and contributes approximately 50% of the total seed-N content (Hanway and Weber, 1971c; Loberg et al., 1984; Vasilas et al., 1995).

Soybean seeds gain more P, on a percentage of the total basis, than N via redistribution from vegetative plant parts (Lauer and Blevins, 1989), indicating that P mobilization may be closely associated with leaf senescence and productivity. Soybean leaves, stems, and pods

translocate 40 to 80% of their P content to the seeds assuming that all of the P disappearing from these organs moved into the seeds (Hammond et al., 1951; Togari et al., 1955). Henderson and Kamprath (1970) reported that at least one-half of the final soybean seed- and pod-P contents were translocated from the vegetative plant parts. The same observation was made by Hammond et al. (1951) who documented that the P content of the pods and seeds increased by 12.8 kg P ha⁻¹ from 87 DAP until maturity (138 DAP) while the P content of other vegetative parts decreased by 7.6 kg P ha⁻¹. This difference in P content contributed about 56-71% of mature seed-P, which was in agreement with results reports by Hanway and Weber (1971c). Hammond et al. (1951) also showed that abscised soybean leaves were almost depleted of P indicating very efficient P translocation. Loberg et al. (1984) reported that soybean leaves are two times more important than pods as a source of P for seeds. However, Crafts-Brandner (1992) conducted a greenhouse experiment with three levels of P fertility (deficient, optimal, and supraoptimal) and found no P translocation from leaves to the developing soybean seeds during reproductive development (R5-8) in one experiment. They summarized that soybean seeds may be developed without P mobilization from the leaves. The results of research referenced in this section suggests that P is usually mobilized from the leaves and translocated to the developing seeds, but mobilization of P and perhaps other nutrients from vegetative structures to the developing seeds may not be needed when the nutrient is highly available or the seed yield (i.e., demand) is very low.

Potassium translocation from vegetative structures to the seeds starts from the leaves and petioles during the seed-filling period (Karlen et al., 1982). According to Sallam et al. (1985), during vegetative growth, K translocates from the main-stem to branches, but during reproductive growth, K translocation occurs from the main-stem to pods, suggesting that soybean stems contribute more K to pods than other plant structures. Drossopoulos et al. (1994), working

on soybean trifoliolate leaves at three different positions (upper, middle, and lowest) on the plant, noted that K remobilizes mainly from the middle and upper leaves to the reproductive sinks. Loberg et al. (1984) stated that soybean leaves translocated three to four times more K to the seeds than pods and both together contributed about 29% of seed-K content. Hanway and Weber (1971c) found that about 50% of the final seed-K content was accounted for by the mobilization of 56% of the K contained in the other plant structures. Hammond et al. (1951) reported that the mobilization of K from the other plant parts of an indeterminate soybean cultivar into the seeds increased when the leaves started to senesce. They determined that on average 78% of K in the mature seeds was translocated from the leaves, stems, and pods. Apparently, the translocation of K contained in soybean leaves to soybean seeds continues as long as the leaves remain on the plant.

Summary

Determinate and indeterminate soybean cultivars possess different growth habits with indeterminate cultivars having a longer flowering to pod set period (R1-4) than determinate cultivars, regardless of maturity group. The total length of the reproductive phase is also 2-3 d or more longer in indeterminate soybean than that of determinate soybean within the same maturity group. The dry matter accumulation pattern in both determinate and indeterminate genotypes is almost similar across time, but indeterminate cultivars accumulate more dry weight from the flowering to pod set period due to having simultaneous vegetative and reproductive growth and a longer flowering to pod set period. Dry matter also distributes differently among the nodes of soybean plants, but the middle nodes produce the greatest dry weight. Only limited information is available describing the duration of each reproductive stage and the dry matter accumulation pattern of determinate and indeterminate soybean grown in the same environment.

Nutrient uptake by soybean is a dynamic process and is very closely related to seed yield and quality. Nitrogen and P uptake by soybean plants is triggered during early-to-mid seed-filling period (R5-6), whereas the peak demand for K occurs from full-bloom (R2) to pod development (R4). At maturity, about 85% N, 83% P, and 68% of the K content in soybean seed is contributed by the mobilization of around 50% of these nutrients from the other plant structures (leaves, petioles, stems, and pods) to the seeds during the seed-filling period. Apparently soybean seed removes about 85% N, 87% P, and 71% K at harvest. The accumulation and distribution of N, P, and K by soybean fluctuates among the main-stem nodes with the greatest K content occurring at the middle nodes. This pattern of K accumulation within main-stem nodes is likely associated with the higher vegetative and reproductive dry matter and N, P, and K accumulation at these middle nodes. The literature contains no information that compares how determinate and indeterminate soybean cultivars having similar or different maturity groups allocate nutrients among nodes and plant parts under the same growing conditions or under different soil-K availability levels. No published research has yet quantified the total nutrient uptake and distribution pattern of glyphosate-resistant soybean cultivars having similar or different maturity groups (especially IV and V).

Nutrient accumulation and partitioning within soybean plants, regardless of growth habit, is highly correlated with the relationship between nutrient concentration and seed yield. The trifoliolate leaf-K concentration at the R1-2 stage is reported to be an excellent indicator of the relative yield potential of soybean with both growth habits; but some scientists have found a poor relationship for indeterminate cultivars. The different relationships may be due to the longer flower and pod set periods coupled with competition for nutrients between the vegetative and reproductive structures of indeterminate soybean. If so, it is reasonable to assume that critical

leaf-K concentrations, the proper plant part to collect tissue samples from, and the best plant development stage for sample collection could differ between growth habits. To monitor K nutrition during the growing season it is required to develop critical trifoliolate leaf-K concentrations across growth stages that are appropriate for soybean having either a determinate or indeterminate growth habit.

Understanding how soybean cultivars, across a range of maturity groups representing both growth habits, allocate nutrients among plant parts would be of value for developing diagnostic tissue sampling protocols for monitoring the plant nutrient status. The dry matter and K accumulation pattern suggests that K deficiency of soybean could be effectively remedied with timely fertilization during the growing season especially before early seed-filling period (R5-6) when the maximum K accumulation occurs. Our overall hypothesis is that the critical leaf-K concentration and the proper growth stage for sampling an indeterminate cultivar will be different from that of a determinate cultivar because plants with an indeterminate growth habit bloom earlier and exhibit concurrent vegetative and reproductive growth that will influence nutrient allocation within the plant. We also hypothesized that the earlier reproductive development would enable the indeterminate cultivars to uptake available soil-K faster or more efficiently, partition a greater proportion of plant K to seeds during the seed-filling period, and possibly utilize plant K more efficiently in seed formation than determinate cultivars grown under K-deficient conditions. Therefore, the objectives of this research are to:

- i. Compare the sensitivity of determinate and indeterminate soybean cultivars to K deficiency.
- ii. Evaluate soybean seed yield and seed nutrient concentrations among nodes of an indeterminate and determinate cultivar grown under different K fertility levels.

- iii. Evaluate season-long dynamics of dry matter and nutrient accumulation and allocation to aboveground plant structures in representative determinate and indeterminate soybean cultivars of same and different maturity groups.
- iv. Determine the actual nutrient harvest index and nutrient mobilization from the aboveground plant structures to seeds of determinate and indeterminate soybean cultivars.
- v. Determine critical K concentrations in the trifoliolate leaves and petioles across reproductive developmental stages of determinate and indeterminate soybean.

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Table 1.1. Critical and sufficient concentrations of different nutrients in recently matured uppermost trifoliolate leaves of soybean plants.

Nutrients	Growth Stage	Concentrations		References
		Critical	Sufficient	
N (g kg ⁻¹)	R1-2		32.5-50.0	Small and Ohlrogge (1973), Keogh et al. (1977), Sabbe et al. (1972), Sabbe et al. (2000)
P (g kg ⁻¹)	R2	3.1		Bell et al. (1995), Sabbe et al. (2000)
	R3	3.5		Melsted et al. (1969)
	R1-2		3.1-5.0	Small and Ohlrogge, (1973), Keogh et al. (1977), Sabbe et al. (1972), Sabbe et al. (2000)
K (g kg ⁻¹)	R2	15.0-21.5		Hanway and Johnson (1985), Bell et al. (1995), Sabbe et al. (2000), Slaton et al. (2010); Clover and Mallarino (2013)
	R3	20.0-21.5		Melsted et al. (1969); de Mooy and Pesek (1970); Sartain et al. (1979)
	R2		17.0-25.0	Sabbe et al. (1972), Small and Ohlrogge (1973); Keogh et al. (1977), Sartain et al. (1979), Grove et al. (1987)
Ca (g kg ⁻¹)	R2	10.2		Hallmark et al. (1990)
	R1-2		10.0-14.0	Sabbe et al. (1972), Keogh et al. (1977), Sabbe et al. (2000)
Mg (g kg ⁻¹)	R3	3.0		Melsted et al. (1969)
	R1-2		3.0-5.5	Sabbe et al. (1972), Keogh et al. (1977)
S (g kg ⁻¹)	R1-2		2.5-6.0	Sabbe et al. (2000)
	R8		≥2.3 in seed	Hitsuda et al. (2004)
Mn (mg kg ⁻¹)	R2	16.0-22.0		Parker et al. (1981), Mascagni and Cox (1985), Bell et al. (1995), Sabbe et al. (2000)
	R8	20.0 in seed		Cox (1968)
	R2		29.0	Cox (1968), Parker et al. (1981)
Zn (mg kg ⁻¹)	R2	15.0-21.0		Ohki (1977), Bell et al. (1995), Sabbe et al. (2000)
	R1-2	32.0-34.0		Hallmark et al. (1990), Hitsuda et al. (2010)
	R8	42.0 in seed		Hitsuda et al. (2010)
B (mg kg ⁻¹)	R2		40.0	Keogh et al. (1977)
	R2	25.0		Hitsuda et al. (2010)
	R2		26.0-60.0	Touchton et al. (1980), Sabbe et al. (2000)
	R8	>25.0 in seed		Reinbott et al. (1997)

Table 1.2. Reported maximum N, P, and K concentrations in the aboveground plant parts of determinate and indeterminate soybean at different growth stages.

Nutrients	Vegetative structures				Reproductive structures			
	Leaf	Petiole†	Stem‡	Stem internode	Total	Pod	Seed	Total
-----g kg ⁻¹ -----								
<u>Determinate soybean</u>								
<u>Growth stage</u>								
	V7-R2	V7-R2	V5-R2	V7	V5			R8
N	50.0§	22.5§	29.0¶	22.5§	31.8#	-	-	54.0#
P	4.0§	2.9§	-	2.2§	2.5#	-	-	5.2#
K	25.0††	47.5††	30.0¶	30.0††	24.2#	-	-	29.9#
<u>Indeterminate soybean‡‡</u>								
<u>Growth stage</u>								
	V4	V4	V4	R8		R4	R8	
N	55.0	25.0	30.0	-	-	40.0	68.0	-
P	3.2	2.1	2.0	-	-	4.0	6.8	-
K	14.0	21.0	16.0	33.0	-	20.0	19.0	-

† Determinate soybean petiole samples included branches.

‡ Determinate soybean stem samples included petioles.

§ Sojka et al. (1989).

¶ Batchelor et al. (1984).

Henderson and Kamprath (1970).

†† Sojka et al. (1985).

‡‡ Hanway and Weber (1971b).

CHAPTER 2

Potassium Fertility Effects Yield Components and Seed Potassium Concentration of Determinate and Indeterminate Soybean

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ABSTRACT

Indeterminate maturity group (MG) IV soybean [*Glycine max* (L.) Merr.] cultivars may be more susceptible to yield loss from K deficiency due to the shorter growing season and earlier onset of reproductive growth than MG V determinate soybean cultivars. Our objective was to identify whether indeterminate MG IV or determinate MG V soybean are affected differently by K deficiency. Seed yield and selected yield components were evaluated from a determinate (MG 5.3) and indeterminate (MG 4.7) soybean cultivar grown under three K fertility levels (low, medium, and high). The trial was conducted in long-term plots that receive 0, 75, or 150 kg K ha⁻¹ yr⁻¹. Yield and yield components of both the determinate and indeterminate cultivars responded similarly to K deficiency. Seed yield for soybean grown with low K averaged 3.4 Mg ha⁻¹ and was 13 to 15% lower than the yields of soybean grown with medium and high K fertility. The yield loss associated with K deficiency was from fewer pods (16-25%) and seeds (22-30%) plant⁻¹, higher seed abortion (5-7%), and lower individual seed weight (8-10%) than soybean with medium or high K fertility. Seed K concentration increased with each increase in K fertility level averaging 15.8, 18.7, and 19.8 g K kg⁻¹ for soybean grown under low, medium, and high K levels, respectively. Regardless of growth habit, the yield loss caused by K deficiency was attributed to the same primary mechanisms of reduced pod number and increased seed abortion.

INTRODUCTION

Soybean is considered to be responsive to K fertilization (Jones et al., 1977). The average seed K concentration of 19.1 g K kg⁻¹ makes the rate of K removal per unit of harvested seed high relative to other grain or oilseed crops (Vitosh et al., 1996; Clover and Mallarino, 2013). Evaluations of the K fertility status of soils in the top 10 soybean-producing states (IL, IA, IN, MN, NE, OH, MO, SD, AR, and ND; USDA-NASS, 2014) in the United States show that, on average, 33% of the soils have soil-test K below the agronomic critical level and soil-test K decreased 15 mg K kg⁻¹ from 2005 to 2010 (IPNI, 2010). The trend for soil-test K to decline suggests that crop yield losses from K deficiency could become more common in intensively cropped fields that receive inadequate K fertilization.

Soybean seed yield can be decreased by more than 50% by K deficiency (Nelson et al., 1946; Jones et al., 1977), but losses of 5 to 20% are more common (Coale and Grove, 1990; Mallarino et al., 1991; Slaton et al., 2010; Clover and Mallarino, 2013). Crop yield loss associated with the physiological effects of K deficiency is partially attributed to reduced assimilate production (Ashley and Goodson, 1972; Sale and Campbell, 1986) and partitioning to the seeds (Ashley and Goodson, 1972; Huber, 1984) due to the reduction in enzymatic activity (Huber, 1984). Potassium deficiency reduces soybean yield by reducing the number of pods plant⁻¹ (Nelson et al., 1946; Jones et al., 1977; Bharati et al., 1986; Coale and Grove, 1990) and seeds pod⁻¹ (Nelson et al., 1946; Coale and Grove, 1990), but may also reduce individual seed weight (Nelson et al., 1946; Bharati et al., 1986).

Soybean yield is highly correlated with the number of seeds produced per unit of area, which is a combination of the secondary yield components of plant population, pods plant⁻¹, and seeds pod⁻¹ (Board et al., 2003; Kahlon et al., 2011). The literature provides insight regarding

how some of these soybean yield components are affected by K nutrition. Sale and Campbell (1987) showed that soybean cultivars may respond differently to K deficiency. However, there is no information comparing how K deficiency influences yield components of the two growth habits, determinate or indeterminate, in the same field production environment.

In many soybean-growing areas of the United States, commercial soybean production is dominated by cultivars having either a determinate (southern United States) or indeterminate growth habit (Midwest). The hectareage in some mid-South soybean-producing states like Arkansas is composed of MG IV cultivars that exhibit indeterminate growth and MG V cultivars that exhibit determinate growth. The yield potential of the two growth habits is usually comparable in the mid-South (Ouattara and Weaver, 1994). The timing of flowering and pod set occurs much earlier, on smaller plants, and for a longer duration for the indeterminate cultivars (Egli and Leggett, 1973). The indeterminate MG IV soybean cultivars tend to have a slightly shorter growing season and may be more susceptible to yield loss from nutrient deficiency than the determinate MG V cultivars. Although we could find no conclusive information for soybean, short-season cotton (*Gossypium hirsutum* L.) cultivars are reported to be more sensitive to K deficiency than long-season cultivars (Tupper et al., 1996; Clement-Bailey and Gwathmey, 2007). The growth differences between determinate and indeterminate soybean cultivars suggest that their response to K deficiency could be different. For example, indeterminate cultivars are characterized as having more main-stem nodes, fewer branches, and fewer total pods plant⁻¹ than determinate cultivars (Wilcox and Frankenberger, 1987; Parvez et al., 1989; Weaver et al., 1991). The secondary yield components that determine seed yield of these two different growth habits could be affected differently by K deficiency.

Nutrient removal in harvested portions of the crop has become an important component of nutrient management. Average grain nutrient concentration is used to estimate the amount of fertilizer nutrient needed to replace what was removed by the harvested crop. Soybean seed K concentrations are known to be affected by K fertility but the response is not consistent (Clover and Mallarino, 2013; Slaton et al., 2013a). Increased grain K concentration appears to be more common when yield increases from K fertilization also occur, but luxury accumulation of K in soybean appears to occur when K is abundantly available.

Our objective was to evaluate the effects of K fertility and soybean growth habit on soybean seed yield, selected yield components (individual seed weight, pods plant⁻¹, seeds plant⁻¹, and seed abortion), and seed K concentration. Specifically, we sought to identify whether yields and yield components of indeterminate or determinate soybean were affected differently by K deficiency. We hypothesized that K deficiency would (i) decrease soybean yield by decreasing individual seed weight, pods plant⁻¹, and seeds plant⁻¹ and by increasing seed abortion resulting in fewer seeds pod⁻¹, (ii) have a more detrimental effect on a MG IV indeterminate cultivar compared to a MG V determinate cultivar due to the shorter growing season coupled with the earlier onset of reproductive growth, and (iii) result in lower seed K concentration.

MATERIALS AND METHODS

Experimental Sites and Treatments

The experiments were conducted in K fertilization trials that were initiated in 2000 and 2001 and offered a range of available soil-K resulting from annually-applied K-fertilizer rates (Table 2.1). Trials were established at the Pine Tree Research Station (PTRS) near Colt, AR, (35°07'17.19" N, 90°57'30.05" W) on a Calhoun silt loam (fine-silty, mixed, active, thermic

Typic Glossaqualf) in 2012 (PTRS-12) and 2013 (PTRS-13). Both research areas were rotated annually with rice (*Oryza sativa* L.).

The experiment at each site contained a total of five K-fertilizer rates that were broadcast annually as muriate of potash to the same plots. The annual application rates at the time these trials were conducted ranged from 0 to 150 kg K ha⁻¹ yr⁻¹ in 37.5 kg K ha⁻¹ increments and contained eight (PTRS-13) or nine (PTRS-12) blocks of each annual-K rate. For the objective of this research, we selected three annual-K rates to represent low (0 kg K ha⁻¹ yr⁻¹), medium (75 kg K ha⁻¹ yr⁻¹), and high (150 kg K ha⁻¹ yr⁻¹) K fertility. The terms low, medium, and high were used to describe the three-annual K rates to reflect the cumulative effect of K fertilization on soil-K availability to plants. We collected plant samples and measured yield in five of the blocks to characterize the effects of K fertility on soybean yield and selected yield components. Each field experiment had a strip-plot treatment structure where annual-K rate was the main-plot (4.0-m wide by 4.9-m long) arranged in a randomized complete block design. The subplot consisted of two glyphosate-resistant soybean cultivars, Armor 48-R40 and Armor 53-R15 (Armor Seed LLC, Jonesboro, AR), having different growth habits and maturities that were strip planted across the annual-K rates. Armor 48-R40 is an indeterminate cultivar (MG 4.7) and Armor 53-R15 is a determinate cultivar (MG 5.3). Each strip-plot contained 10, 38-cm wide rows of each cultivar.

Soil Sampling and Analysis

One composite soil sample composed of five 2-cm diam. soil cores was collected from the 0- to 10-cm depth of each main-plot before application of K fertilizer treatments. Soil samples were oven-dried at 55°C, crushed to pass a 2-mm sieve, extracted with Mehlich-3 solution (Helmke and Sparks, 1996), and the extract was analyzed for nutrient concentrations by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Arcos-160 SOP, Spectro,

NJ). Soil pH was determined in a 1:2 v:v (soil/water) mixture (Sikora and Kissel, 2014). The mean values of selected soil chemical properties for each site are listed by annual-K fertilizer rate in Table 2.2. Soil organic matter content was determined for soil collected from only the 0 kg K ha⁻¹ yr⁻¹ treatment using the weight loss-on-ignition method (Schulte and Hopkins, 1996). Soil organic matter in the 0- to 10-cm soil depth averaged 29 g kg⁻¹ for both PTRS-12 and PTRS-13.

Crop Management

Phosphorus was applied as triple superphosphate (200 g P kg⁻¹) at a rate of 29 kg P ha⁻¹ yr⁻¹ across the study area. Boron (1.1 kg B ha⁻¹) was also broadcast as a granular fertilizer before planting soybean each year (Slaton et al., 2013b). Both sites were flood-irrigated as needed, and irrigation and pest management closely followed the recommendations provided by the University of Arkansas Cooperative Extension Service (University of Arkansas, 2000). Each year soybean was drill seeded into an untilled seedbed. The seeding rate for each site-year and cultivar averaged 73 kg ha⁻¹, which corresponds to a seeding rate of 417,600 seeds ha⁻¹.

Plant Sampling and Analysis

Four whole mature plants that were visually representative of the plant population were collected from the interior rows of each plot at each site-year to evaluate the effect of K fertility on soybean yield, selected yield components, and seed K concentration. The plants were stored at room temperature until they were processed.

The total number of soybean main-stem nodes, nodes on secondary branches, and pods (filled and unfilled) on the four sampled plants were counted and summed to calculate the average number of main-stem nodes, branch nodes, and pods plant⁻¹. Each pod was examined and categorized by the number of filled seed (zero-, one-, two-, three-, or four-seed pods). For PTRS-13, the number of filled and unfilled seed cavities present in each pod (one-, two-, three-,

or four-cavity pods) were counted, which allowed for the calculation of the total percentage of aborted seed $[(\text{total seeds plant}^{-1}/\text{total number of cavities plant}^{-1}) \times 100]$. The percentage of seed abortion from one-, two-, three-, or four-cavity pods was also calculated to identify whether seed abortion was more common in a particular size of pod. The total number of seeds four plants⁻¹ was counted and weighed by discarding the aborted or malformed seeds and expressed as number and yield (weight) of seed plant⁻¹, respectively. The average individual seed weight was also calculated (total seed weight/total seed number). The seeds were stored in an air conditioned laboratory (21°C) for 30 to 60 d before a subsample of 30 whole seeds from each plot was weighed, digested with concentrated HNO₃ and 30% H₂O₂ (Jones and Case, 1990), and digests were analyzed by ICP–AES to determine harvested seed K concentration. The whole-seed moisture content at the time of analysis averaged 80 g H₂O kg⁻¹.

Field seed yield was measured by harvesting 4.5 m² from each subplot with a small plot combine. The weight and moisture of the harvested seed were recorded and final seed yield was calculated based on a seed moisture content of 130 g H₂O kg⁻¹. Seed K removal through harvest was calculated (harvested seed K concentration × field seed yield) and expressed as kg K ha⁻¹.

Statistical Analysis

Data from PTRS-12 and PTRS-13 were analyzed together using the MIXED procedure of SAS (v9.4, SAS Inst., Cary, NC). The statistical model was a strip-plot treatment structure that included the fixed effects of the annual-K rate as the main-plot factor and soybean growth habit as the strip-plot factor and random effects of block and year. The model was changed for seed abortion where year was not included as the data were collected only in 2013.

When a significant *F* test was obtained for any parameter, the means were separated by Fisher's protected LSD at the 0.05 probability level. The studentized residuals distribution and

Cook's *D* statistics were examined for each parameter to identify possible outliers and influential data, respectively. When appropriate, the model was refit by omitting the outliers or influential data.

RESULTS AND DISCUSSION

Soybean Seed Yield

Seed yield plant⁻¹ was similar between determinate and indeterminate cultivars but was affected only by K fertility (Table 2.3). Averaged across soybean growth habits, seed yield plant⁻¹ increased with each increase in K fertility level (Table 2.4). Soybean grown with medium and high K fertility produced seed yields that were 40 and 60%, respectively, greater than the yield of soybean grown with low K treatment. The seed yield plant⁻¹ of soybean grown with high K fertility was 14% greater than soybean with medium K. Seed yield as measured in the field and seed yield plant⁻¹ showed comparable responses to K fertility, but the magnitude of field yield loss attributed to K deficiency was 13 to 15% (Table 2.4) compared to 29 to 38% yield loss from the four, hand-harvested plants. Averaged across K fertility levels, field seed yield was 14% greater for soybean having the indeterminate growth habit (4.0 Mg ha⁻¹) compared to soybean having the determinate growth habit (3.5 Mg ha⁻¹). The yield loss from K deficiency was within the range of yield losses reported in the literature, which typically range from 5 to 20% (Jones et al., 1977; Coale and Grove, 1990; Mallarino et al., 1991; Slaton et al., 2010; Clover and Mallarino, 2013). The yield results show that K deficiency limited overall soybean yield and would allow potential differences to be expressed within the individual components that determine soybean yield.

Soybean Yield Components

Main-stem and Branch Nodes per Plant

We evaluated three yield components, namely the individual seed weight, seed number plant⁻¹, and pod number plant⁻¹ plus the number of main-stem nodes plant⁻¹ and secondary or branch nodes plant⁻¹ to further understand the effect of K fertility on soybean seed yield. Both main-stem and branch nodes plant⁻¹ were affected only by soybean growth habit (Table 2.3). The indeterminate soybean produced more main-stem nodes plant⁻¹ (20.3) and no branch nodes plant⁻¹ (0) compared to the determinate soybean which averaged 13.1 main-stem and 12.6 branch nodes plant⁻¹.

Determinate soybean cultivars are characterized as being shorter, producing fewer main-stem nodes with profuse branching from the lower main-stem nodes, and producing more pods plant⁻¹ than indeterminate cultivars (Beaver and Johnson, 1981; Wilcox and Frankenberger, 1987; Weaver et al., 1991; Ouattara and Weaver, 1995). Our hypothesis was that the simultaneous vegetative and reproductive growth of the indeterminate cultivar might result in different yield component effects as compared to the determinate cultivar, which reaches near maximal plant height and node number before transitioning into reproductive growth (Bernard, 1972). The determinate and indeterminate cultivars selected for this study adhered to the described generalization as the determinate cultivar had fewer main-stem nodes and more lateral branches from the lower nodes. The level of K-deficiency represented in our research did not significantly influence main-stem or branch node number (Table 2.3) and agrees with results reported by Bharati et al. (1986) on the effects of K fertilization on the growth and yield of a determinate soybean cultivar.

Individual Seed Weight

Individual seed weight was influenced by the main effect of K fertility (Table 2.3). Averaged across soybean growth habits, the seed weight was statistically similar for soybean grown with medium or high K levels and 8 to 12% greater than soybean grown with a low K level (Table 2.4). The literature shows that the response of individual seed weight to K fertility is somewhat inconsistent. In research that documented significant yield increases from K fertilization, Nelson et al. (1946) reported significant and dramatic seed yield (137-342%) and individual seed weight increases to K fertilization while others (Bharati et al., 1986; Coale and Grove, 1990; Fernández et al., 2009) reported some numerical individual seed weight differences that were not significantly affected by K fertilization. Specific reasons for the inconsistent individual seed weight response are not clear, but overall seed quality as affected by the severity of K deficiency may be responsible. Nelson et al. (1946) noted that more than one-third of the seeds harvested from the no K control were malformed. Sale and Campbell (1987) reported individual seed weight might increase under moderate K deficiency but was clearly decreased by severe K deficiency. Soybean seed quality issues have been associated with K deficiency on several instances (Crittenden and Svec, 1974; Camper and Lutz, 1977; Jeffers et al., 1982; Vyn et al., 2002). The literature suggests that individual seed weight reduction from K deficiency may occur and contribute to yield loss. Individual seed weight is usually not highly correlated with overall soybean yield (Board et al., 2003; Kahlon et al., 2011) and probably plays a minor role in determining the magnitude of yield loss from K deficiency.

Pods per Plant

The number of pods plant⁻¹ was affected by the main effects of K fertility and soybean growth habit, but not by their interaction (Table 2.3). Pod number plant⁻¹ increased with each

incremental increase in K fertility level (Table 2.4). Soybean grown with high K fertility produced 12% more pods plant⁻¹ than soybean with medium K fertility. Averaged across growth habits, the number of pods plant⁻¹ was increased by 19 and 33% for soybean grown with medium and high K levels, respectively, compared to soybean grown under the low K level. Averaged across K fertility levels, soybean with the determinate growth habit (83 pods plant⁻¹) produced 28% more pods plant⁻¹ compared to the indeterminate growth habit (65 pods plant⁻¹). The literature shows that K fertilization of soybean grown on K-deficient soil consistently increases the number of pods plant⁻¹, but the magnitude of the effect has varied widely (Nelson et al., 1946; Jones et al., 1977; Bharati et al., 1986; Coale and Grove, 1990).

Seeds per Plant

The number of seeds plant⁻¹ was affected only by K fertility (Table 2.3). Seed number plant⁻¹ increased with each increase in K fertility level (Table 2.4). Under high K fertility, soybean plants produced 43 and 12% more seeds plant⁻¹ compared to the low and medium K fertility levels, respectively. Seed number plant⁻¹ has seldom been reported in other research and is the combined influence of pods plant⁻¹ and seeds pod⁻¹. Previously, we described how K fertility influenced the number of pods plant⁻¹, which, on average, accounted for a lower percentage of the calculated differences among K fertility levels suggesting that the pods of K-deficient plants might also contain fewer harvestable seeds. Fernández et al. (2009) showed that K-deficient soybean produced a greater percentage of pods with no harvestable seed and Coale and Grove (1990) showed that the number of pods plant⁻¹, seeds pod⁻¹, and seeds m⁻² were lower in K-deficient soybean suggesting that the incidence of seed abortion might be greater in K-deficient soybean.

Pod Size Distribution

Soybean growth habit, either as a main effect or an interaction, always influenced the percentage of pods in each pod size category (Table 2.5). Likewise, K fertility level either as a main effect or a component of an interaction, influenced the percentage of pods in all pod-size categories except the four-seed pods. The zero-seed pods made up only 0.3 to 6.4% of the total pods and were more common on the determinate soybean within each K fertility level (Table 2.6). The percentage of zero-seed pods was similar among the K-fertility levels for the indeterminate cultivar, but for the determinate cultivar, the percentage of zero-seed pods was greater for the low fertility level than the medium and high K levels which were similar. The percentage of one-seed pods was affected by both the main effects of K fertility and soybean growth habit, where soybean with low K fertility had a greater percentage of one-seed pods than soybean with medium or high K fertility. Averaged across K fertility levels, soybean having the determinate growth habit (19%) had a greater percentage of one-seed pods than the indeterminate growth habit (10%).

The interaction between K fertility and growth habit significantly affected the percentage of total pods that were two- and three-seed pods (Table 2.5). The interaction showed the indeterminate soybean had a lower percentage of two-seed pods at each K fertility level compared to the determinate soybean and within each growth habit the percentage of two-seed pods showed a different trend among K fertility levels (Table 2.6). The percentage of two-seed pods was greater for the indeterminate soybean grown with low K compared to the medium and high K fertility levels, whereas two-seed pods were more common in the medium and high K fertility levels for the determinate soybean. The three-seed pods represented the greatest percentage of pods found on the indeterminate soybean grown with medium and high K fertility. The percentage

of three-seed pods on the determinate soybean was less than on the indeterminate soybean at all K levels and was not affected by K fertility. For the indeterminate soybean, plants grown with medium and high K fertility produced a greater percentage of three-seed pods than when K was low. Regardless of growth habit, four-seed pods were seldom produced, but the determinate soybean produced no four-seed pods (0%) compared to the indeterminate soybean (1.4%).

Previous research has shown no consistent effect of K fertilization on the filled-pod size distribution (Nelson et al., 1946; Fernández et al., 2009). Nelson et al. (1946) showed the absolute number of pods increased as K fertilization increased, but the percentage of pods having two- and three-cavities was not consistently affected by increasing K fertilization rate. Coale and Grove (1990) did not examine specific pod sizes but reported the average number of seeds pod⁻¹ increased from K fertilization. Our results indicate that medium or high K fertility increased the number of pods plant⁻¹ and number of filled seeds pod⁻¹ within the pod size that accounted for the majority of pods. The results suggest K-deficient soybean produces fewer pods and the pods contain a fewer number of harvestable seeds than when K is sufficiently available. The lower number of pods plant⁻¹ suggests that K-deficient soybean does not produce as many blooms and pods, aborts more blooms and pods, or both than K-sufficient soybean. Our research and information within the literature are insufficient to answer which of these results in fewer pods plant⁻¹ and the subject warrants additional research.

Seed Abortion

Seed abortion information was recorded only for the 2013 trial. The percentage of the total seed aborted was affected by the main effects of K fertility and soybean growth habit (Table 2.7). The percentage of total seeds plant⁻¹ that were aborted was greatest for soybean grown with low K (14.4%, LSD 0.05 = 2.3) compared to medium (9.5%) and high (7.3%) K fertility.

Soybean with the determinate growth habit aborted 9.3% of the seeds compared to 11.5% for soybean with the indeterminate growth habit.

We measured seed abortion from one-, two-, three-, or four-cavity pods in trials conducted in 2013 to identify whether seed abortion was more common in a particular pod-size category. A summary of the numerical distribution of seed abortion in each pod-cavity size category is warranted since seed abortion was not always affected by the treatments. The determinate soybean averaged 79 pods plant⁻¹ of which 5% were one-cavity pods, 85% were two-cavity pods, 10% were three-cavity pods, and 0% were four-cavity pods. The indeterminate soybean averaged 64 pods plant⁻¹ with one-, two-, three-, and four-cavity pods comprising 2, 23, 73, and 2% of the total pods, respectively. The seed abortion from the determinate soybean was 0.3% from one-cavity pods, 7.6% from two-cavity pods, 1.4% from three-cavity pods, and 0% from four-cavity pods. The indeterminate soybean aborted 0.03, 2.2, 10.4, and 0.2% of the total seeds from one-, two-, three-, and four-cavity pods, respectively. The numerical trend suggests that a greater percentage of seed abortion occurs in the most common pod size which was two-cavity pods for the determinate cultivar and three-cavity pods for the indeterminate cultivar.

The percentage of seed abortion in one- and four-cavity pods was not affected by K fertility or soybean growth habit, but the K fertility by growth habit interaction was significant for the two- and three-cavity pods (Table 2.7). Potassium fertility had no effect on the percentage of seed abortion in two-cavity pods for the indeterminate soybean (Table 2.8). Seed abortion in two-cavity pods of the determinate soybean cultivar occurred more frequently in the low K level. Seed abortion in two-cavity pods was always greater for the determinate soybean compared to the indeterminate soybean. For the three-cavity pods, the significant interaction showed the percentage of seed abortion within each K fertility level was always greater for the indeterminate

soybean, was uniform and low among K fertility levels for the determinate soybean, and for the indeterminate soybean, abortion decreased incrementally as K fertility increased. Limited information is available in the published literature regarding cavity specific ovule abortion due to K fertility. Nelson et al. (1946) reported that the percentage of filled cavities was uniform among pod cavity sizes and was lowest when K nutrition limited yield. Increased seed abortion plus fewer pods plant⁻¹ appear to be the two most consistent attributes that contribute to yield loss from K deficiency.

Determining the physiological reasons for increased seed abortion was beyond the scope of our research, but the role that K plays in assimilate transport is likely involved. Heitholt et al. (1986) demonstrated that there was no difference in the K concentration of open flowers and immature pods that were either aborted or retained and eventually concluded that flower and pod abortion were due to an insufficient assimilate supply required to meet the demand of the developing flowers and pods. Potassium deficiency has been shown to reduce both total assimilate production (Ashley and Goodson, 1972; Sale and Campbell, 1986) and transport to the reproductive structures (Ashley and Goodson, 1972; Huber, 1984). Research to pinpoint whether the yield loss from K deficiency is node specific or is distributed uniformly across the plant is warranted.

Seed Potassium Concentration and Removal

Potassium concentration in the harvested seeds was influenced by both K fertility and growth habit, but not their interaction (Table 2.5). Seed K concentration increased with each increase in K fertility level averaging 15.8 g K kg⁻¹ for low K, 18.7 g K kg⁻¹ for medium K, and 19.8 g K kg⁻¹ (LSD 0.05 = 0.8) for high K fertility. Seed from soybean exhibiting the determinate growth habit (18.6 g K kg⁻¹) had greater seed K concentration than seed from the indeterminate soybean (17.6 g K kg⁻¹). The K concentration of soybean seed is influenced by both genetics

(Sale and Campbell, 1987) and K nutrition (Nelson et al., 1946). Seed K concentration has been shown to be constant or increase as K fertilization rate increased (Nelson et al., 1946; Farmaha et al., 2011; Clover and Mallarino, 2013; Slaton et al., 2013a). Clover and Mallarino (2013) concluded that grain K concentration response to K fertilization was more common in soybean than corn (*Zea mays* L.), but was somewhat unpredictable for both crops and showed no strong association with grain yield response to K fertilization. The published literature suggests that seed K concentration is most likely to be increased by K fertilization when K deficiency occurs and limits seed yield. Luxury consumption of K with the resultant effect of increasing seed K concentration without a yield increase has been reported (Clover and Mallarino, 2013). Our results also suggest that increasing seed K concentration without a significant yield increase is possible.

Potassium removal by harvested seed was affected only by K fertility (Table 2.5). The amount of K removed by harvested seed was similar for soybean having medium (73 kg K ha^{-1} , $\text{LSD } 0.05 = 6$) and high (78 kg K ha^{-1}) K fertility and both had greater K removal than soybean grown with low K (54 kg K ha^{-1}) fertility.

CONCLUSIONS

The primary questions addressed by our research were (i) what soybean yield components are affected by K deficiency and (ii) does K deficiency effect yield components of determinate and indeterminate soybean the same? The unique aspect of our research was that it compared the response of two soybean cultivars representing each of the two growth habits to K deficiency. Field-measured yield loss attributed to K deficiency ranged from 13 to 15% and is likely representative of losses from soybean fields that exhibit hidden hunger or late-season symptoms of K deficiency. Our results were in agreement with a limited amount of published literature showing that the yield loss associated with K deficiency is primarily from fewer seeds

plant⁻¹ due to fewer pods plant⁻¹ and a higher incidence of seed abortion which led us to accept our first hypothesis. Our results also showed additional yield loss resulted from reduced seed weight when soybean was grown under low K fertility. Based on these whole-plant assessments with single soybean cultivars representing each of the two growth habits, determinate and indeterminate, soybean from both growth habits responded similarly to K deficiency in regards to their individual seed weight, pods and seeds plant⁻¹, and percent of total seed abortion suggesting that our second hypothesis (the MG IV indeterminate soybean cultivar would be more sensitive to K deficiency than the MG V determinate soybean cultivar) should be rejected. Finally, our results supported the third hypothesis and indicated that seed K concentration would be lower when K fertility was limited and may continue to increase as the rate of K fertilization exceeds the rate needed to maximize seed yield. Luxury removal of K is an issue in forage K fertilizer recommendations but has seldom been mentioned as a concern in fertilization of row crops.

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Table 2.1. Selected agronomic and site-year specific information for two soybean trials conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12) and 2013 (PTRS-13).

Site-year	Year established	Annual-K rate [†]			Date planted
		0	75	150	
		-----Cumulative, kg K ha ⁻¹ ‡-----			day/month
PTRS-12	2001	0	786	1572	26 April
PTRS-13	2000	0	917	1834	16 May

[†] 0, 75, and 150 kg K ha⁻¹ yr⁻¹ represent low, medium, and high K fertility production environments, respectively.

[‡] The values listed indicate the cumulative amount of K applied to the plots since the trials were established. The initial annual K fertilization rates were 0, 56, and 112 kg K ha⁻¹ yr⁻¹ which were changed to 0, 75, and 150 kg K ha⁻¹ yr⁻¹, respectively after 2006.

Table 2.2. Selected soil chemical property means of long-term K fertilization trials at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12) and 2013 (PTRS-13).

Annual-K rate†	Soil pH	Mehlich-3 extractable soil nutrients							
		P	K	SD‡	Ca	Mg	S	Mn	Zn
kg K ha ⁻¹ yr ⁻¹		-----mg kg ⁻¹ -----							
		<u>PTRS-12</u>							
0	7.6	28	61	5	2423	404	21	283	9
75	7.6	30	81	9	2383	392	21	260	11
150	7.8	28	91	8	2274	384	22	282	11
		<u>PTRS-13</u>							
0	7.6	26	67	12	2212	374	21	193	11
75	7.6	21	74	4	2078	360	21	194	19
150	7.5	24	78	8	1929	368	21	173	17

† 0, 75, and 150 kg K ha⁻¹ yr⁻¹ represent low, medium, and high K fertility production environments, respectively.

‡ SD, standard deviation for the mean of soil-test K concentration.

Table 2.3. Analysis of variance *P* values for soybean seed yield, field seed yield, main-stem node number, branch node number, individual seed weight, pod number, and seed number for research conducted at the Pine Tree Research Station in 2012 and 2013.

Source of variation	df	Seed yield	Field seed yield	Main-stem node number	Branch node number	Individual seed weight	Pod number	Seed number
		g plant ⁻¹	Mg ha ⁻¹	-----no. plant ⁻¹ -----		g seed ⁻¹	-----no. plant ⁻¹ -----	
K fertility (K)	2	<0.001	0.001	0.176	0.286	<0.001	<0.001	<0.001
Growth habit (GH)	1	0.208	0.026	<0.001	<0.001	0.212	<0.001	0.270
K × GH	2	0.883	0.651	0.062	0.286	0.714	0.280	0.938

Table 2.4. Soybean seed yield, field seed yield, individual seed weight, pod number, and seed number as affected by K fertility level for research conducted at the Pine Tree Research Station in 2012 and 2013.

K fertility level†	Seed yield g plant ⁻¹	Field seed yield Mg ha ⁻¹	Individual seed weight g seed ⁻¹	Pod number -----no. plant ⁻¹ -----	Seed number
Low	15	3.4	0.121	63	122
Medium	21	3.9	0.131	75	157
High	24	4.0	0.135	84	175
LSD(0.05)	2	0.3	0.005	7	15

† As characterized by the application of 0, 75, and 150 kg K ha⁻¹ yr⁻¹ to represent low, medium, and high K fertility production environments, respectively.

Table 2.5. Analysis of variance *P* values for the percentage of zero-, one-, two-, three-, and four-seed pods, seed K concentration, and K removal through harvest for research conducted at the Pine Tree Research Station in 2012 and 2013.

Source of variation	df	Filled seed pod ⁻¹ category†					Seed K concentration g K kg ⁻¹	K removal through harvest kg K ha ⁻¹
		Zero-seed pods	One-seed pods	Two-seed pods	Three-seed pods	Four-seed pods		
		-----%-----						
K fertility (K)	2	<0.001	0.001	0.812	<0.001	0.062	<0.001	<0.001
Growth habit (GH)	1	<0.001	<0.001	<0.001	<0.001	<0.001	0.008	0.276
K × GH	2	<0.001	0.642	<0.001	0.002	0.062	0.282	0.317

† The filled seed pod⁻¹ categories represent the actual number of harvestable seed in each pod. For example, zero-seed pods represent all pods, regardless of the number of ovule cavities that contained no harvestable, filled seed.

Table 2.6. Percentage of zero-, one-, two-, and three-seed pods as affected by the interaction of K fertility level × soybean growth habit for zero-seed pods, by K fertility level for one-seed pods, and by the interaction of K fertility level × soybean growth habit for two- and three-seed pods for research conducted at the Pine Tree Research Station in 2012 and 2013.

K fertility level†	Zero-seed pods‡		Two-seed pods		Three-seed pods		
	Determinate	Indeterminate	One-seed pods	Determinate	Indeterminate	Determinate	Indeterminate
	-----%						
Low	6.4	0.8	18	67	43	5	41
Medium	2.7	0.4	13	73	38	6	52
High	2.6	0.3	12	75	37	7	54
LSD(0.05)§	0.9		3		5		4
LSD(0.05)¶	0.9		-		5		4

† As characterized by the application of 0, 75, and 150 kg K ha⁻¹ yr⁻¹ represent low, medium, and high K fertility production environments, respectively.

‡ Zero-seed pods, a pod, regardless of the number of ovule cavities, that contains no harvestable, filled seed; one-, two-, and three-seed pods, define pods that contain one-, two-, and three-filled seed, respectively.

§ LSD compares the means among K fertility levels within a growth habit or averaged across growth habits.

¶ LSD compares the means among K fertility levels and growth habits.

Table 2.7. Analysis of variance *P* values for soybean total seed abortion and seed abortion from one-, two-, three-, and four-cavity pods for research conducted at the Pine Tree Research Station in 2013.

Source of variation	df	Seed abortion				
		Total	One-cavity pods†	Two-cavity pods	Three-cavity pods	Four-cavity pods
		-----%				
K fertility (K)	2	<0.001	0.450	0.002	<0.001	0.227
Growth habit (GH)	1	0.026	0.075	<0.001	<0.001	0.070
K × GH	2	0.113	0.519	0.030	0.001	0.227

† Pod cavity size categories indicate the potential maximum number of seed that a pod could contain. For example, a one-cavity pod contains one cavity and can contain only one-filled seed and a four-cavity pod can contain a maximum of four-filled seeds.

Table 2.8. Percentage of seed abortion from two- and three-cavity pods as affected by the interaction effects of K fertility level × soybean growth habit for research conducted at the Pine Tree Research Station in 2013.

K fertility level†	Seed abortion			
	Two-cavity pods‡		Three-cavity pods	
	Determinate	Indeterminate	Determinate	Indeterminate
	-----%-----			
Low	10.9	3.1	1.4	12.8
Medium	5.8	1.5	1.7	9.5
High	6.0	1.5	1.2	5.3
LSD(0.05)§		1.9		1.8
LSD(0.05)¶		2.0		1.8

† As characterized by the application of 0, 75, and 150 kg K ha⁻¹ yr⁻¹ to represent low, medium, and high K fertility production environments, respectively.

‡ A two-cavity pod is defined as a pod that contains two cavities and can contain a maximum of two-filled seed. If a pod contains two-filled seed it would also be a two-seed pod, but can also be a zero-, or one-seed pod if seed abortion occurs. A three-cavity pod is defined as a pod that contains three cavities and can contain a maximum of three-filled seed and can be classified as a zero-, one-, two-, or three-seed pod.

§ LSD compares the means among K fertility levels within a growth habit.

¶ LSD compares the means among K fertility levels and growth habits.

CHAPTER 3

Soybean Yield Components and Seed Potassium Concentration Responses among Nodes to Potassium Fertility

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ABSTRACT

Soybean [*Glycine max* (L.) Merr.] yield loss by K deficiency has been reported extensively, but very little research that has evaluated how the yield loss is distributed among nodes. We evaluated soybean seed yield, individual seed weight, pod and seed numbers, seed abortion, and seed-K concentration among nodes of an indeterminate and determinate cultivar grown under three K fertility levels (low, medium, and high represented by 0, 75, and 150 kg K ha⁻¹ yr⁻¹, respectively). Chlorosis along upper leaf margin was observed during seed-filling period in every low K fertility plot. Soybean grown with medium and high K fertility averaged 28 and 43%, respectively, greater predicted seed yield on the top seven (of ten) node segments for the indeterminate soybean and 72 and 101% greater seed yield on the node segments 2, 3, 4, and 7 (of seven) for the determinate soybean compared to plants having low K fertility. Yield loss was attributed to reduced individual seed weight, fewer numbers of pods and seeds, and increased seed abortion. The seed-K concentration of soybean grown with low K fertility was lowest [11.6 (indeterminate) and 15.2 (determinate) g K kg⁻¹] for seeds located on the top nodes and increased (17.8 g K kg⁻¹) quadratically to the bottom of the plant. The largest proportion of seed yield and the greatest yield loss from K deficiency come from the middle and upper nodes of indeterminate plants and the combination of the bottom nodes, due to branching, plus the upper-middle nodes of determinate plants.

INTRODUCTION

The distribution of soybean yield and yield components among nodes is important information for modeling growth, identifying yield-limiting factors, and predicting soybean yield (Ramseur et al., 1984). Several studies have shown that soybean yield and yield components among nodes of both determinate and indeterminate cultivars vary due to the differences in water availability (Carlson et al., 1982; Ramseur et al., 1984), row spacing (Herbert and Litchfield, 1982; Ramseur et al., 1984), plant density (Dominguez and Hume, 1978; Liu et al., 2010), light interception (Liu et al., 2010), and soybean genotypes (Hansen and Shibles, 1978; Wiebold et al., 1981). The literature suggests that the differences in seed yield and yield components among treatments tends to be more evident on the upper one-half of soybean plants (Weil and Ohlrogge, 1976; Carlson et al., 1982; Herbert and Litchfield, 1982; Ramseur et al., 1984). However, seed yield and yield components of the lower nodes of determinate soybean also vary since branches originate from these lower nodes and contribute substantially to seed yield (Ramseur et al., 1984).

Soybean seed yield and yield components are reported to be influenced by K fertilization, especially on soils with low K fertility. Potassium deficiency can cause substantial yield loss in both determinate and indeterminate soybean (Coale and Grove, 1990; Mallarino et al., 1991; Slaton et al., 2010; Clover and Mallarino, 2013; Parvej et al., 2015) by decreasing the pods plant⁻¹, seeds pod⁻¹, seeds plant⁻¹, and individual seed weight and by increasing seed abortion (Nelson et al., 1946; Jones et al., 1977; Bharati et al., 1986; Coale and Grove, 1990; Parvej et al., 2015). Despite the large number of papers investigating soybean yield response to K fertilization, we could find no research that has evaluated whether the effects of K deficiency on yield loss and yield components are distributed uniformly across soybean plant nodes.

Based on the concept of nutrient mobility, the classical K deficiency symptoms on plant leaves should occur as an irregular yellowing (chlorosis) along the leaf margins with symptoms being worse on the lower leaves since K is mobile within the plant (Sinclair, 1993). However, during reproductive growth, K deficiency symptoms are frequently observed on the middle and upper (young) leaves of soybean (Jeffers et al., 1982; Sale and Campbell, 1986; Snyder and Ashlock, 1996) and cotton (*Gossypium hirsutum* L.; Maples et al., 1988; Oosterhuis, 2002) plants rather than the lower, older leaves. The appearance of K deficiency symptoms in the middle and upper soybean canopy during the pod set and seed-filling periods indicates the complexity of K mobilization and that source-sink relationships involving K are complex and warrants further investigation.

The actual reason of K deficiency symptoms on the upper leaves of soybean has not been clearly elucidated. The results of Wrona and Epstein (1985) showed that less than one-half of the ^{86}Rb -labeled K^+ was allocated to the aboveground shoot, and less than 10% was recovered in leaf blades, of two tomato species [*Lycopersicon esculentum* Mill. cv Walter and *Lycopersicon cheesmanii* spp. *minor* (Hook)] suggesting impaired K translocation. Limited literature suggests that the rate of K translocation from the lower, older leaves to the upper leaves may not be sufficiently rapid to meet the high K demand during the seed-filling period resulting in K deficiency symptoms on the upper soybean leaves (Jeffers et al., 1982). Hanway and Weber (1971) showed that leaf-, petiole-, and stem-K concentrations of indeterminate soybean cultivars declined more from the top portion of the plant than from the middle and lower plant portions during the seed-filling period (R5-7; Fehr et al., 1971), which coincides with the growth period with the greatest K demand. They also showed that the K concentration of mature pods produced on the upper third of the stem was significantly lower than the K concentration of pods produced

on the lower third of the stem. Sadler et al. (1991) revealed that the K concentration of mature pods (with seeds) gradually decreased with some fluctuations from the bottom to the top of the stem for a cultivar having a determinate growth habit. Collectively, the literature suggests K deficiency symptoms in the middle and upper leaves indicate the supply of K is insufficient to meet the demand of both leaves and seeds and the seed-K concentration is lowest on the upper nodes.

Nutrient removal by harvested grain is important information for fertilizer recommendations. Many fertilization recommendations follow the ‘build and maintain’ philosophy that includes a nutrient replacement component in the rate equation (Vitosh et al., 1996; Hochmuth et al., 2014). The variation of pod (with or without seed) K concentration among nodes (Hanway and Weber, 1971; Sadler et al., 1991) suggests that the amount of K removed from a particular soybean field could vary with the K concentration of seeds collected from different portions of the plant. A better understanding of how K is allocated among seeds at different node positions may help develop more efficient fertilization practices or lead to improved methods for monitoring plant K nutrition and yield potential.

Our primary objective was to evaluate soybean seed yield, individual seed weight, pod and seed numbers, seed abortion, and seed-K concentration among nodes of an indeterminate and determinate cultivar grown under different K fertility levels. We hypothesized that when K availability was low K deficiency would increase in severity during seed-filling and at nodal positions with the largest number of pods due to limited active K uptake and mobilization from vegetative tissues to seeds. Hence, we predicted that i) K deficiency would decrease soybean yield, individual seed weight, and pod and seed numbers and increase seed abortion on the middle to the upper portions of the indeterminate plants and lower and upper portions of the branching determinate plants and ii) regardless of soybean growth habit, seed-K concentration at

each node segment would increase with each increase in K fertility level and would be greatest for seed produced on the lower nodes of the plant and decrease gradually towards the upper nodes of the plant.

MATERIALS AND METHODS

The response of soybean yield components and seed-K concentration among nodes to K fertilization was evaluated on a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualf) at the Pine Tree Research Station near Colt, AR, USA (35°07'17.19" N latitude and 90°57'30.05" W longitude) in 2012 and 2013. A detailed description of the experimental sites, treatment structure, soil sampling and analysis methods, crop management, and plant sampling and analysis was published by Parvej et al. (2015). Briefly, two glyphosate-resistant soybean cultivars, Armor 48-R40 [indeterminate growth habit and maturity group (MG) 4.7] and Armor 53-R15 (determinate growth habit and MG 5.3) were strip planted across three annual-K fertilization rates (0, 75, and 150 kg K ha⁻¹ yr⁻¹ representing low, medium, and high K fertility levels, respectively). The terms low, medium, and high K fertility represent the cumulative soil-K availability to plants by annual-K fertilization and soil-test K index (Parvej et al., 2015). The experiment was a strip-plot with five blocks where K fertilization rate was the main-plot and soybean cultivar was the strip-plot that contained ten, 38-cm wide rows of each cultivar. Soybean was planted into an untilled seedbed on 26 April in 2012 and 16 May in 2013. The seeding rate (73 kg ha⁻¹ i.e. 417,600 seeds ha⁻¹), irrigation, and pest management closely followed recommendations provided by the University of Arkansas Cooperative Extension Service (University of Arkansas, 2000).

Four plants of each cultivar were collected from each plot at maturity to evaluate seed yield, selected yield components, and seed-K concentration as affected by main-stem and branch

node locations and K fertility levels. The nodes of the sampled plants were numbered from the topmost node (node 1) to the bottom node. The four sampled plants were dissected from the top of the plant to the bottom and tissues from the four plants were composited into a single sample. The indeterminate cultivar had an upright growth habit, no lateral branches, and 18 (2013) to 20 (2012) main-stem nodes plant⁻¹ at maturity. The determinate plant was a bushy plant, had 12 (2013) to 14 (2012) main-stem nodes plant⁻¹ at maturity, and contained multiple branches that also contained pods. Nodes on the lower one-half of the determinate cultivar contained at least one primary branch that had 5 to 6 nodes. Each plant was dissected by cutting immediately above the main-stem nodes (from top to bottom) 3, 5, 7, 9, 11, 13, 15, 17, and 19 so that each sample (node segment) consisted of two nodes and two internodes. Tissues from each dissected node segment were separated into i) stem internodes, ii) pods, and iii) seeds to evaluate soybean seed yield, selected yield components such as individual seed weight, pod and seed numbers, and seed abortion, and seed-K concentration responses among nodes to K fertility. Branches were dissected by node with nodes counted from the top of the branch towards the main-stem node and separated into the same plant components as described for the main-stem.

Each pod from each node segment was also examined and categorized by the number of filled and unfilled seed cavities (one-, two-, three-, or four-cavity pods) to calculate the total percentage of seed abortion from the 2013 study (Parvej et al., 2015). The distribution of the total percentage of seed abortion among node segments [$(\text{total number of unfilled cavities node}^{-1} \text{ segment} \div \text{total number of cavities plant}^{-1}) \times 100$] was also evaluated. The seeds were counted and weighed from each node segment after discarding the aborted and/or malformed seeds. For evaluating seed-K concentration at different main-stem and branch node segments, a subsample of three whole seeds from each main-stem and branch node segment was weighed, digested

(Jones and Case, 1990), and analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES). For the determinate cultivar, some lower main-stem node segments did not contain any seed, but did contain a branch. The seed-K concentration for main-stem node segments that produced no pods was replaced by the seed-K concentration of the branch node segment closest to the main-stem node segment.

Statistical Analysis

Data for the determinate and indeterminate cultivars were analyzed separately because of their different growth habits (e.g., branches vs. no branches). Replicate data of each variable was regressed across node segments using a statistical model (MIXED procedure of SAS v9.4, SAS Inst., Cary, NC) that included the linear, quadratic, and cubic node segment terms and their interaction with K fertility level as fixed effects. Block and year were included as random effects. The model was refined for each variable by eliminating the most complex nonsignificant ($P > 0.10$) model term in a stepwise fashion until the simplest model with all significant model terms was obtained. The studentized residuals distribution was examined for possible outliers (studentized residual $> \pm 2.5$) and the model was refit by omitting the outliers when appropriate. When a significant F-test was obtained for any variable, the means were separated by LSMEANS and DIFF statements at each node segment at the 0.05 probability level.

RESULTS AND DISCUSSION

Potassium Deficiency Symptom

Chlorosis along the margins of lower soybean leaves was observed on only a few plants shortly before the R1 (flowering) stage for both the indeterminate and determinate cultivars grown in soil having low K fertility. The leaf-K deficiency symptoms within the low K fertility treatments became more common on the upper leaves as the season progressed. During the seed-

filling period (R5-7), the yellowing of leaf margins was observed on the upper leaves of soybean plants grown in every low K fertility plot, and the visual symptoms were more severe for the early-maturing indeterminate growth habit than the late-maturing determinate growth habit. Although we could not find any information for soybean, Halevy (1976) found more frequent K deficiency symptoms on an early-maturing cotton cultivar than on a late-maturing cultivar. No K deficiency symptoms were visible at any time during the growing season on soybean grown in the medium and high K fertility soil in either year.

Soybean Seed Yield

We previously reported that seed yield plant⁻¹ was 40 to 60% greater for soybean grown with medium and high K fertility levels, respectively, compared to the seed yield plant⁻¹ of soybean grown with low K fertility (Parvej et al., 2015). The primary research objective reported in this paper was to determine how K availability influenced the yield at each node segment. Regression analysis showed that soybean seed yields were different among node segments and were significantly affected by K fertility level for both the indeterminate and determinate cultivars (Table 3.1; Fig. 3.1a, b). For the indeterminate cultivar, seed yield was a cubic function of node segment that differed among K fertility levels. Seed yield on the top seven node segments (1-7) was affected by K fertility level where soybean grown with medium and high K fertility produced, on average, 28 and 43%, respectively, greater predicted seed yield than soybean grown with low K fertility (Fig. 3.1a). The predicted seed yield on node segments 1 through 5 averaged 13% greater in the high K fertility compared to soybean grown with medium K fertility. Regardless of K fertility level, the largest proportion (55-60%) of the seed yield was produced on the middle four node segments (4-7) where seed yield was increased, on average, 18 to 27% by the medium and high K fertility levels.

For the determinate cultivar, seed yield was a cubic function of main-stem node segment that differed among K fertility levels (Table 3.1). The predicted soybean seed yield was different among K fertility levels on node segments 2, 3, 4, and 7 (bottommost) on which plants grown with medium and high K fertility produced similar yields that were, on average, 72 and 101%, respectively, greater than the seed yield produced by soybean grown with low K fertility (Fig. 3.1b). Regardless of K fertility level, the greatest proportion (51-63%) of seed yield came from node segments 2, 3, and 7 (bottom) where seed yield averaged 77 to 104% greater for soybean grown with medium and high K fertility than low K fertility.

The determinate soybean cultivar produced branches from the bottom two main-stem node segments with each branch having 5 to 6 nodes. Branches contributed 25 to 32% of the total seed yield. The seed yield of branches showed a quadratic relationship across node segments that differed among K fertility levels (Table 3.2). The predicted branch seed yield averaged 99 and 133% greater on the middle portion of the branches (node segments 2 through 5) for soybean grown with medium and high K fertility, respectively, compared to soybean grown with low K fertility (Fig. 3.2a). There was no difference in predicted seed yield between the medium and high K fertility treatments for the same node segment across branch node segments.

The distribution of soybean seed yield across node segments of both the indeterminate and determinate cultivars was similar to the seed yield distribution across nodes reported by Carlson et al. (1982), Herbert and Litchfield (1982), Scott et al. (1983), Ramseur et al. (1984), and Sadler et al. (1991). We could find no other research showing soybean seed yield variation among nodes due to K fertilization in the literature, but our results agree with other research showing the effects of stand density, row spacing, and irrigation on seed yield across nodes. For example, seed yield of an indeterminate soybean cultivar varied by 24 to 31% on the lower-

middle nodes and 13 to 38% on the middle to upper nodes due to differences in plant density and row spacing (Weil and Ohlrogge, 1976; Herbert and Litchfield, 1982) and 24 to 36% on the lower-middle to upper-middle nodes due to soil-moisture stress (Carlson et al., 1982). Ramseur et al. (1984) reported that the overall seed yield of a determinate cultivar was increased 170 to 199% by irrigation, but the largest difference in seed yield (228-344%) occurred on the upper nodes. The literature coupled with our findings indicate that the largest proportion of seed yield plant⁻¹ comes from the middle and upper-middle nodes of the indeterminate plants and the combination of the bottom node, due to branching, plus the nodes on the top one-half of the determinate plants. Nodes that produce the greatest proportion of seed yield are also the nodes most affected by stress resulting from nutrient deficiencies, drought, and perhaps other stresses.

Individual Seed Weight

Individual seed weight was a cubic function of node segment, which depended on K fertility level for both the indeterminate and determinate cultivars (Table 3.1; Fig. 3.3a, b). The indeterminate soybean cultivar grown with medium and high K fertility had, on average, 12 and 15%, respectively, greater predicted individual seed weights on the top five node segments and 5 and 10% lower individual seed weights on the bottom three node segments compared to plants with low K control (Fig. 3.3a). The predicted individual seed weight averaged 4% greater on the top three node segments and 5% lower on the bottom three node segments under high K fertility than medium K fertility. Individual seed weights were similar among K fertility levels for node segments 6 and 7.

The determinate soybean cultivar grown with medium and high K fertility had similar predicted individual seed weights on the top six node segments that averaged 12 and 14%, respectively, greater than the seed weight of soybean grown with low K fertility (Fig. 3.3b).

Regardless of growth habit, the individual seed weight of soybean is known to vary among nodes, differ among cultivars, and be affected by crop management and stress conditions (Weil and Ohlrogge, 1976; Carlson et al., 1982; Ramseur et al., 1984). Nelson et al. (1946) and Sale and Campbell (1987) reported individual seed weight reduction by K deficiency, but their research lacks in showing how the individual seed weight reduction is distributed among nodes.

Seed and Pod Numbers

Soybean seed and pod numbers were cubic function of node segment for both the indeterminate and determinate cultivars, respectively (Table 3.1; Fig. 3.4a-d). On the top five node segments of the indeterminate cultivar, the predicted seed number increased, on average, 13% as fertility level increased from medium to high fertility and 25% as fertility increased from low to medium fertility (Fig. 3.4a) and pod number increased by 14% with each increase in K fertility level (Fig. 3.4c). On node segments 6 and 7, the number of seeds was statistically similar for plants grown with medium and high K fertility, but averaged 13 and 19%, respectively greater than plants grown with low K fertility (Fig. 3.4a). The number of pods on node segments 6 and 7 averaged 14% greater for plants grown with high K compared to low K fertility (Fig. 3.4c). Like soybean seed yield, the largest proportion (54-59%) of predicted seed and pod numbers came from the middle four node segments (4-7) of the indeterminate plants where seed and pod numbers were increased, on average, 14 to 22% and 8 to 17%, respectively, due to medium and high K fertilization.

For the determinate cultivar, the predicted seed and pod numbers were influenced by K fertility on node segments 2 through 4 and 7 (the bottommost node segments; Fig. 3.4b, d). The greatest percentage (51-63%) of seeds and pods were produced on node segments 2, 3, and 7 where plants grown with medium and high K fertility had statistically similar values that

averaged 62 and 91%, respectively, more seeds and 56 and 80% more pods than soybean grown with low K fertility. On node segment 4, plants grown with high K fertility produced 59% more seeds and 57% more pods than soybean having low K fertility.

The literature clearly shows that the numbers of seeds and pods vary among nodes, are affected by a number of factors, and the trends across nodes are different for cultivars having indeterminate and determinate growth habits. For soybean with an indeterminate growth habit, Carlson et al. (1982) showed that the major differences exhibited between irrigated and non-irrigated plants occurred on nodes located on the middle to the upper-middle portion of the plant. For the determinate soybean, Ramseur et al. (1984) showed irrigation resulted in seed and pod number differences on the upper one-half of the main-stem nodes as well as on the lower nodes only when seeds and pods of lower main-stem nodes and branch nodes were combined. Regardless of soybean growth habit, K fertilization, irrigation, and perhaps other factors influence seed and pod numbers on those node locations where the largest number of seeds and pods are produced and seed yield differences occurred. Our research did not address the dynamics of fewer seeds and pods plant⁻¹ to know whether flowers or pods were aborted at a higher rate or never formed. Such information would be useful in developing effective strategies for managing in-season K deficiency (e.g., how K fertilizer timing influences yield).

Seed Abortion

The percentage of seed abortion was a quadratic function of node segment for the indeterminate cultivar and a cubic function of node segment for the determinate cultivar and, like most other variables, seed abortion was affected by K fertility level (Table 3.1; Fig. 3.5a, b). Significant differences in predicted seed abortion among K fertility levels occurred at node segments 2-7 of the indeterminate cultivar (Fig. 3.5a) and node segments 1-4 of the determinate

cultivar (Fig. 3.5b). Nodes that experienced the greatest abortion rate (nodes 2 and 3 for the determinate and nodes 4, 5, and 6 for the indeterminate cultivar) were also the greatest yielding node segments (Fig. 3.1) suggesting the competition for K and other nutrients among developing seed is likely to occur where the demand is greatest. There were no differences in abortion (Fig. 3.5) or yield (Fig. 3.1) on the lowest nodes of each cultivar (e.g., growth habit) perhaps because the nodes are located on the lowest part of the stem where they receive preferential access to K. We did not find any research that has investigated the effect of K deficiency or any other stress on soybean flower, pod, or seed abortion across nodes. Research has demonstrated that soybean flower, pod, or seed abortion increases due to stress resulting from K deficiency (Nelson et al., 1946), drought (Westgate and Peterson, 1993), and increased plant density (Weil and Ohlrogge, 1976).

Seed Potassium Concentration

Soybean seed-K concentrations for each cultivar (growth habit) was a quadratic function of node segment that depended on K fertility level (Table 3.1; Fig. 3.6a, b). Regardless of soybean growth habit, seed-K concentration increased with each increase in K fertility level, and the predicted seed-K concentration at each node segment was different among K fertility levels. Seed-K concentrations increased quadratically from the top to the bottom nodes of the plant for the determinate soybean grown with low K fertility and for the indeterminate soybean grown with low and medium K fertility. The linear and quadratic slope coefficients for seed-K concentrations of the indeterminate soybean grown with high K fertility and determinate soybean grown with medium and high K fertility were not different from zero indicating that seed-K concentration was uniform among node segments with mean concentrations (intercept values) of 18.5 to 20.4 g K kg⁻¹ (Table 3.1). For soybean grown with low K fertility, the predicted seed-K concentrations from the top to bottom node segments ranged from 11.6 to 17.8 g K kg⁻¹ for the

indeterminate cultivar (Fig. 3.6a) and 15.2 to 17.8 g K kg⁻¹ for the determinate cultivar (Fig. 3.6b). Although the two soybean growth habits were not statistically compared, the numerical values suggest that seed-K concentration is more variable in the indeterminate cultivar. The results for each growth habit clearly indicate the seed-K concentrations among nodes are more variable when K availability is limiting.

Seed-K concentrations of the branches of the determinate soybean also increased linearly for each K fertility level from the top to bottom branch node segments (Table 3.2; Fig. 3.2b). Regardless of K fertility level, seed-K concentration increased at the same linear rate (0.210 g K kg⁻¹ node⁻¹ segment) from the top (branch node 1) to the bottom (branch node 6) of the branch but the intercept values increased with each increase in K fertility level.

The decline of seed-K concentration from the bottom towards the top of the main-stem or branch node segment agree with the findings of Hanway and Weber (1971; indeterminate soybean) and Sadler et al. (1991; determinate soybean). Our results support these findings and indicate that the range of seed-K concentrations on soybean plants can be decreased or eliminated by increasing K availability. Results from the literature and the low and medium K fertility levels in our research indicate that soybean seeds produced on the lower nodes receive K preferentially over seed produced on the middle and upper nodes of main-stems and branches. Foliar feeding of K during the pod set and fill stages may be useful in minimizing seed-K concentration differences from the top to bottom of the plant, but the amount of K needed to equalize seed-K concentrations among nodes may be impractical to apply to plant leaves, especially if the yield response to foliar K is minimal or if ample preplant-applied K can maximize yield (Nelson et al., 2005). Aside from providing ample K to prevent K deficiency and maximize yield, other benefits of minimizing seed-K concentrations differences among nodes are

currently unknown and warrants further research. Seed-K concentrations have been shown to be positively correlated with seed oil ($R = 0.48-0.64$) and total isoflavone concentrations ($R = 0.57-0.76$) and negatively correlated with seed protein concentration ($R = 0.67-0.78$; Vyn et al., 2002; Yin and Vyn, 2003).

The rapid decline of seed-K concentration towards the upper canopy under low K fertility helps explain why K deficiency symptoms commonly appear on the middle and upper canopy during reproductive growth. The developing seed is a strong sink for K and other nutrients. For example, Vasilas et al. (1980) showed that mature soybean seeds contained about 94% of the ^{15}N applied at the R5 to R7 growth stages. Several researchers have noted that during reproductive growth, N and K concentrations decrease from all soybean plant parts except the seed (Hanway and Weber, 1971; Barber, 1978; Batchelor et al., 1984; Sallam et al., 1985), suggesting active accumulation, mobilization of K from vegetative structures, or both to soybean seed, the dominant sink. Hanway and Weber (1971) showed that late in the growing season, soybean leaf-K concentration declined more from nodes located on the top one-third of the stem than from nodes located on the middle and lower one-third of the stem for an indeterminate soybean. A similar observation was made by Drossopoulos et al. (1994), who noted that K mobilizes mainly from the middle and upper leaves rather than the lower leaves to the reproductive sinks. Ohlrogge (1960) and Jeffers et al. (1982) hypothesized that the rate of K translocation from the lower, older leaves to the upper leaves may be impaired or may not be sufficiently rapid to meet the high K demand during the seed-filling period (R5-7). Soybean uptake of K from the soil is most rapid during reproductive growth and peaks at the R6 growth stage (Bender et al., 2015). The large seed-K concentration range among nodes is likely from the combination of active K uptake and transport to the strongest sinks plus mobilization of K from vegetative plant

structures to the developing seeds. Egli and Leggett (1973) showed that the flowering to pod set period (R1-4) of an indeterminate MG IV soybean cultivar was 6-8 d longer than that of a determinate cultivar having the same MG rating. The early initiation of pod and seed set of indeterminate cultivars from the lowest nodes may give the seed on the lower nodes a competitive advantage for K and other nutrients in the early season, but be a disadvantage for seed set on the middle and upper nodes later in the growing season, especially when K is limited.

CONCLUSIONS

Our primary research goal was to determine how K deficiency influences the distribution of seed yield among nodes of determinate and indeterminate soybean cultivars. The greatest proportion of soybean yield, regardless of K fertility level, was produced by nodes on the top two-thirds of the indeterminate cultivar and the combination of the bottom node, due to branching, plus the nodes on the top one-half of the determinate cultivar. The yield loss from K deficiency was greatest on the nodes that produced the largest proportion of seed yield for each growth habit. Previous research has shown this for other plant stresses (e.g., drought), but our research is the first to show the node positions where yield loss from K deficiency occurs. Thus, our results were consistent with our first prediction that K deficiency would affect yield components to a greater extent in the middle to upper portion of an indeterminate cultivar and the lower and upper portions of a determinate cultivar. The yield loss on the top nodes was from reduced individual seed weight, fewer number of pods and seeds, and increased seed abortion.

Our results were also consistent with our second prediction that for K-deficient soybean there would be a large seed-K concentration gradient from the top to bottom of the plant with seed-K being greatest for seed produced on the bottom nodes and least for seed produced by the top nodes. The K concentration of seed collected from the upper nodes or the seed-K

concentration gradient between the top and bottom nodes might be useful in diagnosing K deficiency at maturity in fields that showed no visible K deficiency symptoms (i.e., hidden hunger) or K deficiency symptoms were not observed because the field was not scouted thoroughly during the season. Maintaining moderate to high K fertility in soil minimizes the seed-K gradient among nodes and increases seed-K concentration. Maintaining high soil K fertility may minimize the seed-K gradient but it may also lead to seed-K accumulation and greater crop K removal without a corresponding yield increase.

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Table 3.1. Coefficients of polynomial models used for predicting seed yield, individual seed weight, seed and pod numbers, seed abortion, and seed-K concentration among main-stem node segments of indeterminate and determinate soybean cultivars from research conducted at the Pine Tree Research Station in 2012 and 2013.

K fertility level†	Polynomial model‡ coefficients									
	Indeterminate					Determinate				
	Intercept	Linear	Quadratic	Cubic	R ²	Intercept	Linear	Quadratic	Cubic	R ²
<u>Seed yield (g node⁻¹ segment)</u>										
Low	-0.937	1.7807	-0.2505	0.0080	0.64	2.697§	0.9725§	-0.5118§	0.0520§	0.48
Medium	0.031§	1.6851	-0.2505	0.0080		-2.203§	7.8609	-2.5653	0.2248	
High	0.606§	1.6177	-0.2505	0.0080		-3.878	9.5913	-2.9875	0.2579	
SE¶	0.325	0.2319	0.0497	0.0031		1.414	1.4073	0.4062	0.0347	
<u>Individual seed weight (g seed⁻¹)</u>										
Low	0.083	0.0194	-0.0027	0.00013	0.33	0.143	-0.0235	0.0051	-0.00029§	0.40
Medium	0.107	0.0160	-0.0027	0.00013		0.164	-0.0254	0.0051	-0.00029§	
High	0.117	0.0141	-0.0027	0.00013		0.172	-0.0269	0.0051	-0.00029§	
SE	0.006	0.0031	0.0007	0.00004		0.007	0.0069	0.0020	0.00017	
<u>Seed number (seeds node⁻¹ segment)</u>										
Low	-2.857§	11.4539	-1.5242	0.0382§	0.65	18.974§	11.2350§	-4.9111§	0.4689§	0.48
Medium	2.825§	10.9176	-1.5242	0.0382§		-20.790§	63.1974	-20.1629	1.7424	
High	6.722	10.4996	-1.5242	0.0382§		-36.513	78.5162	-24.1804	2.0899	
SE	2.326	1.5667	0.3290	0.0203		10.637	10.6559	3.0532	0.2585	
<u>Pod number (pods node⁻¹ segment)</u>										
Low	0.008§	4.3430	-0.5865	0.0145§	0.65	9.654§	7.4932§	-3.1321§	0.2963	0.51
Medium	1.440§	4.2036	-0.5865	0.0145§		-12.149	35.4082	-11.2446	0.9683	
High	3.162	4.0138	-0.5865	0.0145§		-19.900	42.5146	-13.0351	1.1209	
SE	0.912	0.6214	0.1306	0.0081		5.548	5.6766	1.6361	0.1358	
<u>Seed abortion (%)</u>										
Low	0.374§	1.1196	-0.1305	NS#	0.54	-4.746	9.0247	-2.7349	0.2281	0.68
Medium	0.477§	0.5697	-0.0660	NS		-2.044§	3.7224	-1.0416	0.0799§	
High	0.706§	0.2782§	-0.0378	NS		-1.017§	2.6393§	-0.6931§	0.0479§	
SE	0.392	0.1831	0.0179			1.364	1.5550	0.4976	0.0470	

Table 3.1. (Cont.)

K fertility level†	Polynomial model‡ coefficients									
	Indeterminate					Indeterminate				
	Intercept	Linear	Quadratic	Cubic	R ²	Intercept	Linear	Quadratic	Cubic	R ²
	<u>Seed-K concentration (g K kg⁻¹)</u>									
Low	10.222	1.4293	-0.0676	NS	0.68	13.579	1.8261	-0.1742	NS	0.57
Medium	16.605	0.7295	-0.0402	NS		18.516	0.5609§	-0.0514§	NS	
High	19.869	0.0200§	0.0213§	NS		20.348	0.1606§	0.0065§	NS	
SE	1.448	0.1941	0.0179			1.298	0.3338	0.0436		

† The terms low, medium, and high K fertility represent the cumulative soil-K availability to plants by annual-K fertilization of 0, 75, and 150 kg K ha⁻¹ yr⁻¹, respectively and soil-test K index.

‡ Quadratic model equation, $y = z + ax + bx^2$ and cubic model equation, $y = z + ax + bx^2 + cx^3$; where y, independent variable; x, main-stem node segment; z, intercept; a, linear coefficient; b, quadratic coefficient; and c, cubic coefficient.

§ Coefficients are not significantly different from zero at the 0.05 probability level.

¶ SE, Standard error of the model coefficients.

Cubic coefficients are not significant at the 0.10 probability level.

Table 3.2. Coefficients of the polynomial models used for predicting branch seed yield and seed-K concentration across branch node segments of a determinate soybean cultivar from research conducted at the Pine Tree Research Station in 2012 and 2013.

K fertility level†	Polynomial model‡ coefficients			R ²
	Intercept	Linear	Quadratic	
	<u>Branch seed yield (g node⁻¹ segment)</u>			
Low	0.368§	0.0286§	-0.0131§	0.18
Medium	0.180§	0.3276	-0.0551	
High	-0.063§	0.4977	-0.0739	
SE¶	0.254	0.1363	0.0207	
	<u>Branch seed-K concentration (g K kg⁻¹)</u>			
Low	16.418	0.2099	NS#	0.58
Medium	19.164	0.2099	NS	
High	20.624	0.2099	NS	
SE	0.373	0.0901		

† The terms low, medium, and high K fertility represent the cumulative soil-K availability to plants by annual-K fertilization of 0, 75, and 150 kg K ha⁻¹ yr⁻¹, respectively and soil-test K index.

‡ Quadratic model equation, $y = z + ax + bx^2$; where y, independent variable; x, branch node segment; z, intercept; a, linear coefficient; and b, quadratic coefficient.

§ Coefficients are not significantly different from zero at the 0.05 probability level.

¶ SE, Standard error of the model coefficients.

Quadratic coefficients are not significant at the 0.10 probability level.

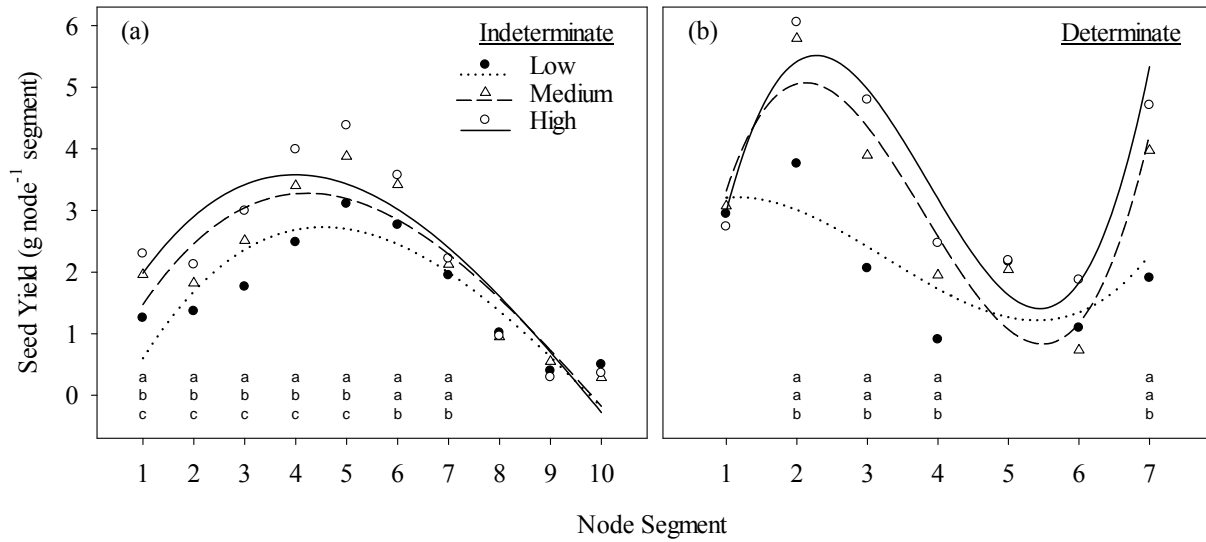


Fig. 3.1. Seed yield across node segments of an indeterminate (a) and determinate (b) soybean cultivar as affected by K fertility level and predicted with a polynomial model for research conducted at the Pine Tree Research Station in 2012 and 2013. Node segment ‘1’ is the top two consecutive nodes and ‘7’ (determinate) or ‘10’ (indeterminate) is the bottom two consecutive nodes. Different letters within the same node segment represent significant predicted seed yield differences among K fertility levels at the 0.05 probability level. Top letter for each node segment represents the top trend line. Predicted seed yield was not significant among K fertility levels at the 0.05 probability level on node segments 8, 9, and 10 for the indeterminate cultivar (a) and on node segments 1, 5, and 6 for the determinate cultivar (b). Coefficient values are listed in Table 3.1.

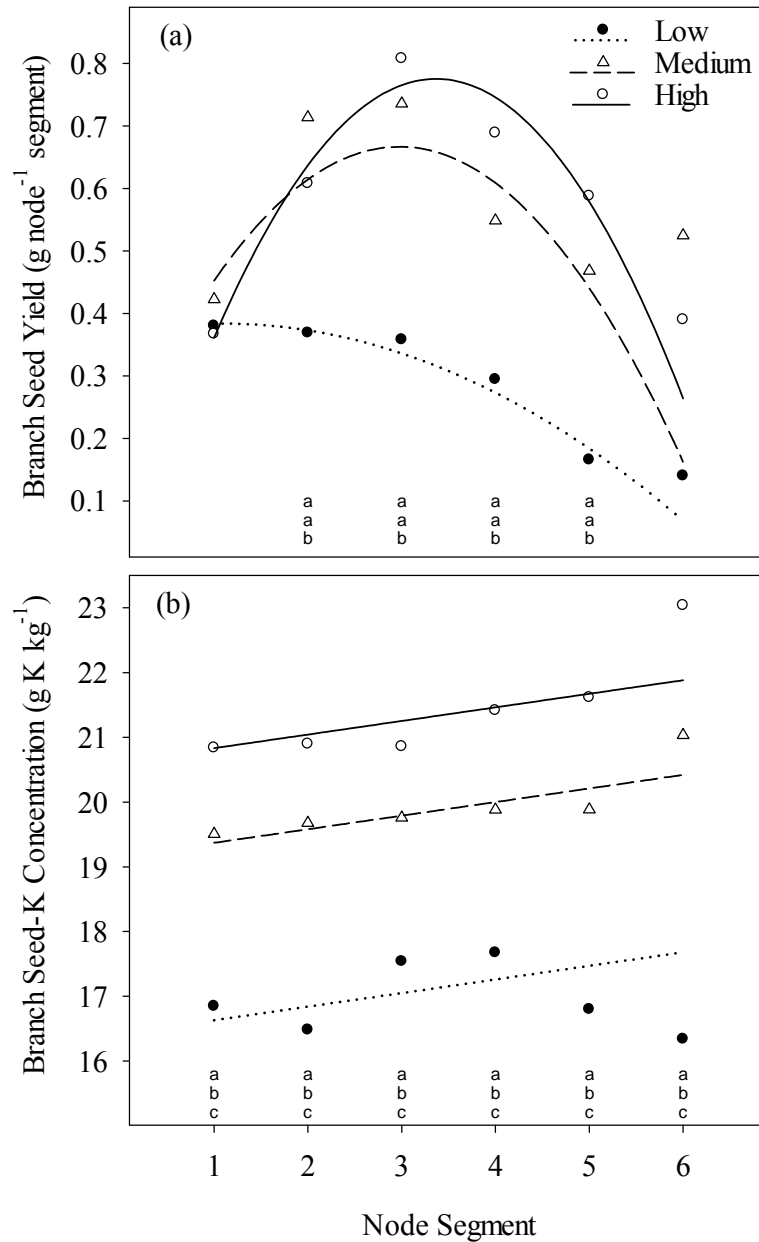


Fig. 3.2. Seed yield (a) and seed-K concentration (b) across branch node segments of a determinate soybean cultivar as affected by K fertility level and predicted with a polynomial model for research conducted at the Pine Tree Research Station in 2012 and 2013. Variables were measured from branches produced from the 5th (2013) and 7th (2012) main-stem node segments. Branch node segment '1' is the topmost node and '6' is the bottommost node close to the main-stem node segment. Different letters within the same node segment represent significant predicted seed yield and seed-K concentration differences among K fertility levels at the 0.05 probability level. Top letter for each node segment represents the top trend line. Predicted seed yield (a) was not significant among K fertility levels at the 0.05 probability level on branch node segments 1 and 6. Coefficient values are listed in Table 3.2.

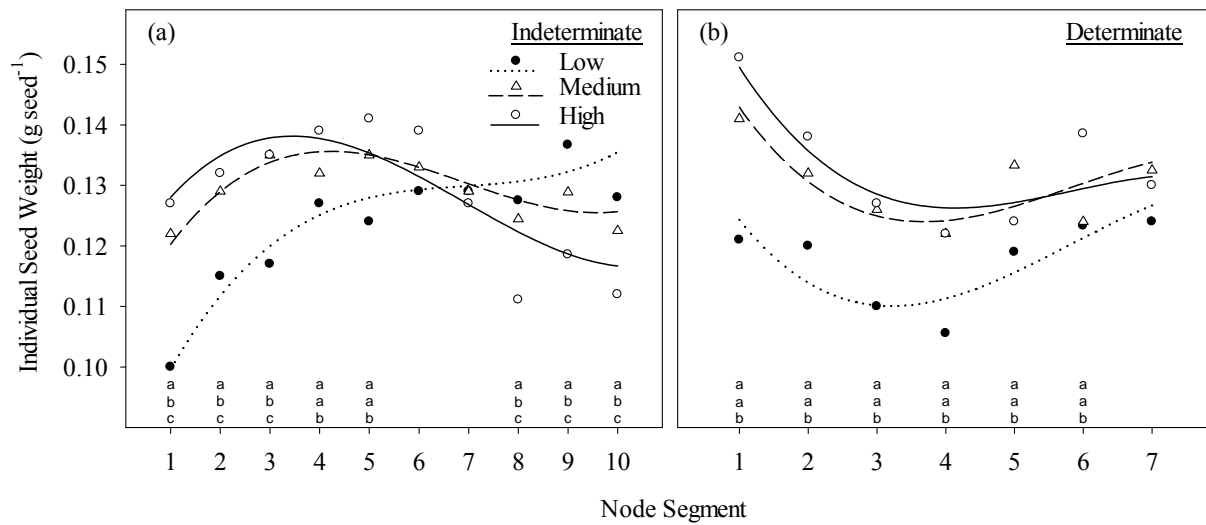


Fig. 3.3. Individual seed weight across node segments of an indeterminate (a) and determinate (b) soybean cultivar as affected by K fertility level and predicted with a polynomial model for research conducted at the Pine Tree Research Station in 2012 and 2013. Node segment ‘1’ is the top two consecutive nodes and ‘7’ (determinate) or ‘10’ (indeterminate) is the bottom two consecutive nodes. Different letters within the same node segment represent significant predicted individual seed weight differences among K fertility levels at the 0.05 probability level. Top letter for each node segment represents the top trend line. Predicted individual seed weight was not significant among K fertility levels at the 0.05 probability level on node segments 6 and 7 for the indeterminate cultivar (a) and on node segment 7 for the determinate cultivar (b). Coefficient values are listed in Table 3.1.

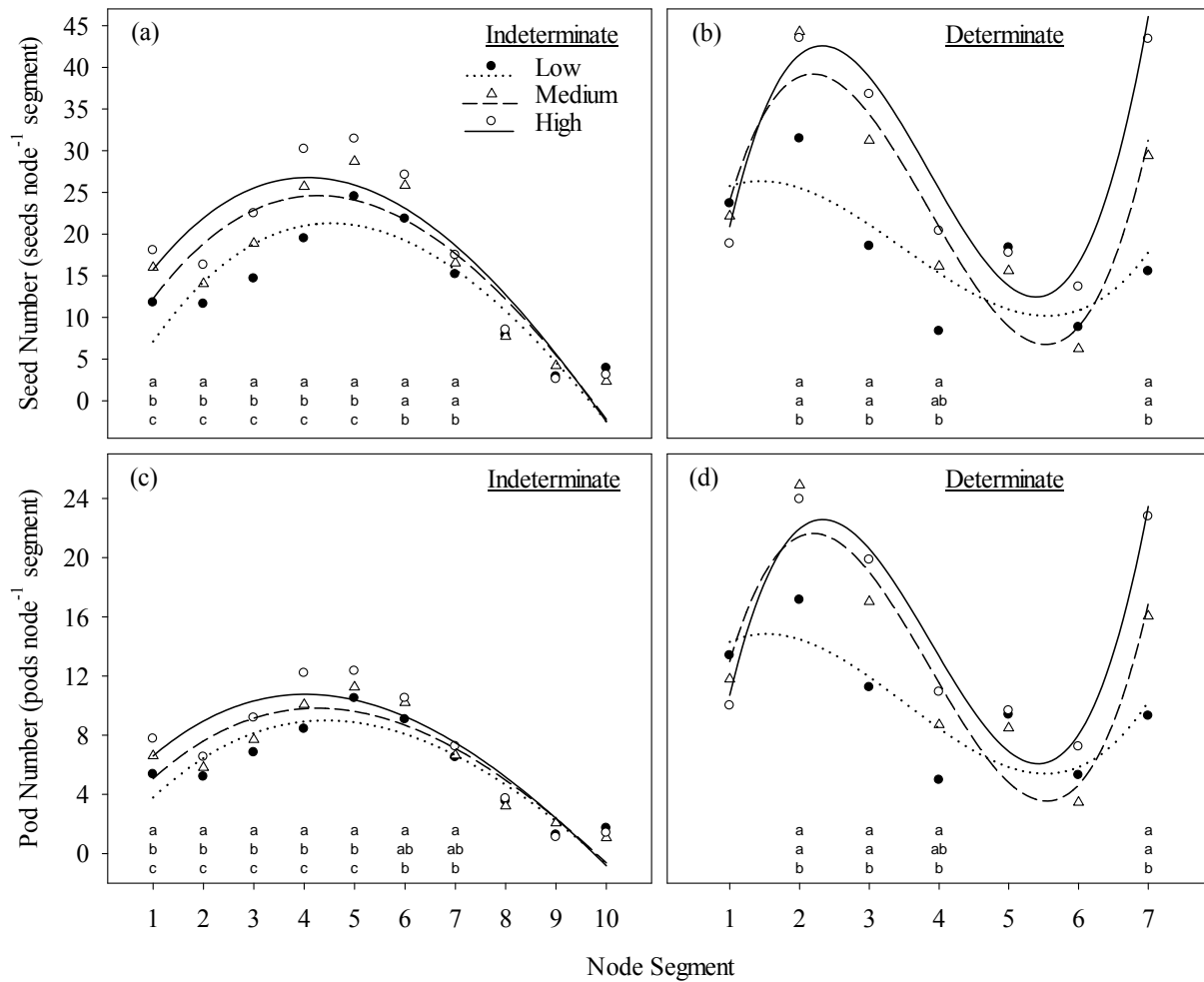


Fig. 3.4. Seed (a-b) and pod numbers (c-d) across node segments of an indeterminate and determinate soybean cultivar as affected by K fertility level and predicted with a polynomial model for research conducted at the Pine Tree Research Station in 2012 and 2013. Node segment '1' is the top two consecutive nodes and '7' (determinate) or '10' (indeterminate) is the bottom two consecutive nodes. Different letters within the same node segment represent significant predicted seed and pod number differences among K fertility levels at the 0.05 probability level. Top letter for each node segment represents the top trend line. Predicted seed and pod numbers were not significant among K fertility levels at the 0.05 probability level on node segments 8, 9, and 10 for the indeterminate cultivar (a, c) and on node segments 1, 5, and 6 for the determinate cultivar (b, d). Coefficient values are listed in Table 3.1.

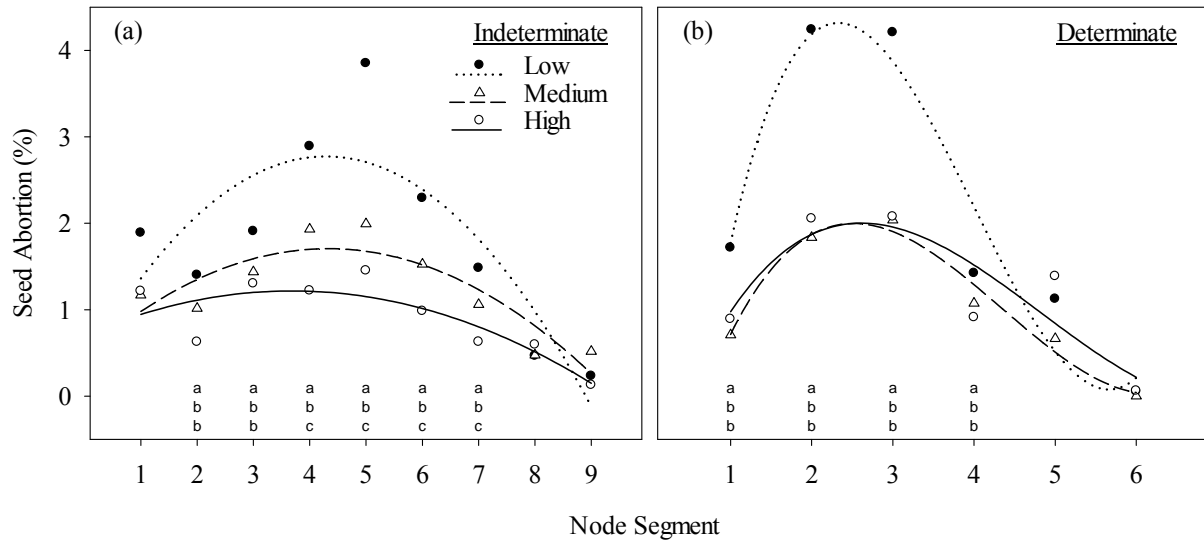


Fig. 3.5. Seed abortion across node segments of an indeterminate (a) and determinate (b) soybean cultivar as affected by K fertility level and predicted with a polynomial model for research conducted at the Pine Tree Research Station in 2013. Node segment ‘1’ is the top two consecutive nodes and ‘6’ (determinate) or ‘9’ (indeterminate) is the bottom two consecutive nodes. Different letters within the same node segment represent significant predicted seed abortion differences among K fertility levels at the 0.05 probability level. Top letter for each node segment represents the top trend line. Predicted seed abortion was not significant among K fertility levels at the 0.05 probability level on node segments 1, 8, and 9 for the indeterminate cultivar (a) and on node segments 5 and 6 for the determinate cultivar (b). Coefficient values are listed in Table 3.1.

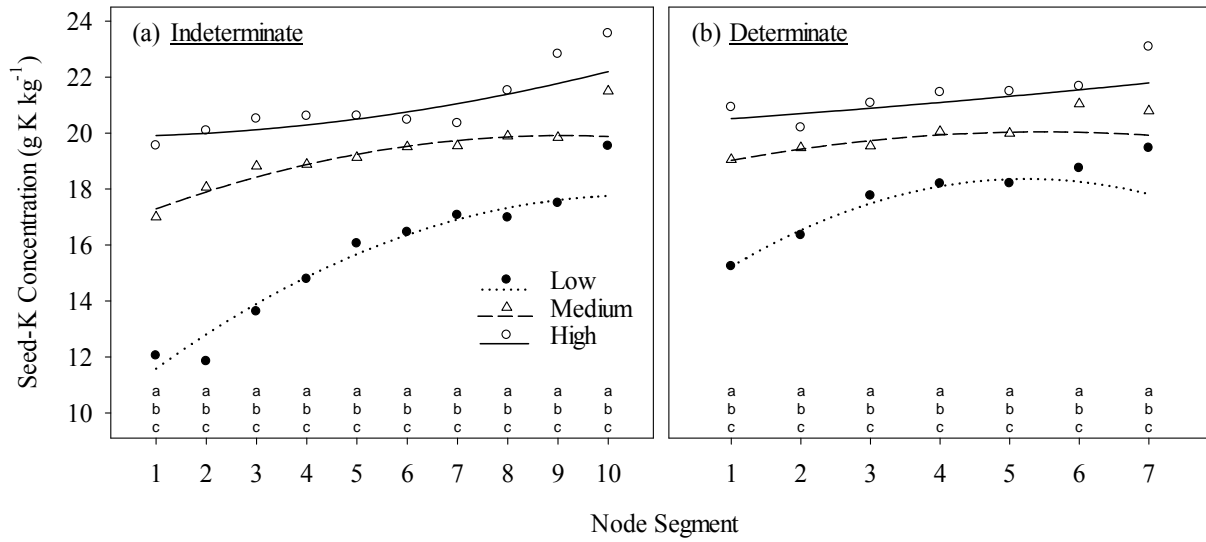


Fig. 3.6. Seed-K concentration across node segments of an indeterminate (a) and determinate (b) soybean cultivar as affected by K fertility level and predicted with a polynomial model for research conducted at the Pine Tree Research Station in 2012 and 2013. Node segment '1' is the top two consecutive nodes and '7' (determinate) or '10' (indeterminate) is the bottom two consecutive nodes. Different letters within the same node segment represent significant predicted seed-K concentration differences among K fertility levels at the 0.05 probability level. Top letter for each node segment represents the top trend line. Coefficient values are listed in Table 3.1.

CHAPTER 4

Dry Matter and Potassium Accumulation and Partitioning in Determinate and Indeterminate Soybean

ABSTRACT

Understanding the uptake and distribution of nutrients among plant structures and growth stages is required to develop diagnostic information to assess plant nutritional health. We evaluated season-long dynamics of dry matter and K accumulation and allocation to aboveground plant parts in soybean [*Glycine max* (L.) Merr.] cultivars representing the 3.9, 4.7, and 5.3 or 5.5 maturity groups (MG) during 2012 and 2013. Whole-plant samples were collected 8 to 10 times between V5 and maturity and partitioned into leaves, petioles, stems and branches, pods, and seeds. Soybean produced a new node every 3 to 4 d until maximum node number was reached. Despite occasional differences in aboveground dry matter, maximum aboveground-K accumulation was similar (131 kg K ha^{-1}) among cultivars and occurred at the R5.5-6.0 stages. Short-season indeterminate cultivars (MG 3.9 and 4.7) had higher K accumulation rates than the long-season determinate cultivar (MG 5.3/5.5) during the early reproductive stages (R1-4). The predicted peak K accumulation rate occurred at the R3-4 stage for all cultivars in both years. In 2012, the peak K accumulation rate for both indeterminate cultivars ($2.2 \text{ kg K ha}^{-1} \text{ d}^{-1}$) was similar and higher than the determinate cultivar ($2.1 \text{ kg K ha}^{-1} \text{ d}^{-1}$). In 2013, the maximum K accumulation rate decreased as the duration of growing season (MG) increased with averages of 2.6, 2.5, and $1.9 \text{ kg K ha}^{-1} \text{ d}^{-1}$ for the MG 3.9, 4.7, and 5.5 cultivars, respectively. The difference in K accumulation rates among cultivars did not affect K mobilization to the developing seeds. Soybean yields were not different among cultivars within each year and averaged 3953 (2012) or 2968 (2013) kg ha^{-1} . The petiole-K concentration was highest among vegetative structures early in the growing season and declined linearly with plant development suggesting that petioles might be a good tissue for monitoring plant K nutrition during the growing season.

INTRODUCTION

Soybean cultivars are classified according to their growth habit, indeterminate or determinate, and maturity group (MG). Indeterminate cultivars are usually classified into MG 000 to IV and are grown primarily in the northern USA. Determinate cultivars are classified as MG V to X and are grown in the southern USA. In Arkansas, a mid-South soybean-producing state, soybean hectares are a blend of cultivars having indeterminate and determinate growth habits ranging from late MG III to mid MG V cultivars. The length of the soybean growth cycle declines as the MG number declines regardless of planting date (Zhang et al., 2004). The main difference between the two growth habits is determinate cultivars cease vegetative growth at or soon after the onset of flowering while indeterminate plants continue vegetative growth for several weeks after flower initiation (Bernard, 1972). An indeterminate cultivar will begin flowering (R1) earlier than a determinate cultivar belonging to the same MG (Egli and Leggett, 1973). Although the duration of the entire reproductive phase (R1-8) is comparable, the duration of some specific reproductive stages varies between growth habits (Wilcox and Frankenberger, 1987). Within the same MG, the flowering (R1-2) period for indeterminate cultivars lasted 3 to 5 d longer (Wilcox and Frankenberger, 1987) and the flowering to pod set (R1-4) period was 6 to 8 d longer (Egli and Leggett, 1973) than determinate cultivars grown in the same environment. However, the total seed-filling period (R5-7) for the determinate cultivar was 3-4 d longer than the indeterminate soybean (Wilcox and Frankenberger, 1987).

The simultaneous vegetative and reproductive growth of indeterminate soybean has been hypothesized to be detrimental to pod set and grain yield due to competition for assimilates between vegetative and reproductive sinks (Hicks and Pendleton, 1969; Egli and Leggett, 1973). Research, mostly with MG III and IV cultivars shows that determinate and indeterminate

genotypes accumulate dry matter in a similar pattern across time with peak dry matter accumulation occurring at the R6-7 stage (Egli and Leggett, 1973; Beaver et al., 1985). Compared to determinate soybean, indeterminate soybean accumulates more dry matter from flowering (R1) to pod set (R4) due to the simultaneous vegetative and reproductive growth and longer flowering and pod set periods (Egli and Leggett, 1973). The assimilate competition between vegetative and reproductive sinks does not appear to impart a consistent and significant dry matter or seed yield advantage for either growth habit (Egli and Leggett, 1973; Beaver and Johnson, 1981; Beaver et al., 1985; Ouattara and Weaver, 1994). However, the effect of the different growth habits and duration on nutrient uptake and allocation among plant structures for a range of cultivars produced in the same environment has not been adequately researched.

Understanding the uptake and distribution pattern of nutrients among plant structures during the growing season is required to develop sound fertilization programs and diagnostic information to assess plant nutritional health. Information for interpreting the nutritional status of soybean is available for only a single growth stage, R1-2 (Keogh et al., 1977; Sabbe et al., 2000). Soybean is known to be responsive to K fertilization when grown in soil with moderate to low K availability. Plants require a large amount of K for proper water balance, nutrient uptake, photosynthesis, and assimilate partitioning (Pettigrew, 2008). Potassium deficiency is perhaps the most common nutrient deficiency of soybean.

Research conducted mostly with indeterminate MG II cultivars or determinate MG VI and VII cultivars show that K uptake and dry matter accumulation are parallel processes that peak at the R6-7 growth stage (Hammond et al., 1951; Henderson and Kamprath, 1970; Hanway and Weber, 1971d; Sallam et al., 1985; Sadler et al., 1991). Soybean uptake of K early in the growing season tends to be slow, but K uptake rate increases sharply and peaks during the R3-4

stage (Hanway and Weber, 1971d; Harper, 1971; Flannery, 1986; Sadler et al., 1991; Bender et al., 2015). The pattern of K uptake suggests that the source-sink relationship and growth differences during the early reproductive phase (R1-4) could influence the stage at which K uptake rate and accumulation peak among cultivars having different growth habits and MG. We are aware of no research that has quantified aboveground-K uptake and distribution patterns among plant structures of modern soybean cultivars representing determinate and indeterminate growth habits and a range of maturity groups (especially late MG III to mid MG V) under the same growing environment.

The overall research goal was to improve our ability to monitor and assess the nutritional status of determinate and indeterminate soybean cultivars by enhancing our understanding of aboveground dry matter and nutrient uptake and allocation patterns during the growing season. The objectives of this study were to i) evaluate season-long dynamics of dry matter and K accumulation and allocation to aboveground plant parts and ii) determine dry matter and K mobilization from the aboveground plant structures to seeds in representative determinate and indeterminate soybean cultivars from a range of MG under the same growing conditions. We hypothesized that i) the total aboveground dry matter and K uptake patterns would be similar for both the determinate and indeterminate cultivars, ii) the times of peak dry matter and K uptake would be growth stage specific, and iii) the earlier reproductive development and longer flowering to pod set period (R1-4) would enable the indeterminate cultivars to accumulate dry matter and K faster and increase dry matter and K mobilization to the seeds compared with the determinate cultivars.

MATERIALS AND METHODS

Experimental Site

Experiments were conducted at the Pine Tree Research Station located near Colt, AR, USA (35°07'23.10" N latitude and 90°55'46.45" W longitude) on a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs) in 2012 and Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) in 2013. Both research areas had been cropped to soybean the previous year.

Before fertilizer application, a composite soil sample was collected from the 0- to 10-cm soil depth from each of four blocks. The soil samples were oven-dried at 55°C and crushed to pass a 2-mm sieve, extracted with Mehlich-3 solution (Helmke and Sparks, 1996), and the extract was analyzed for nutrient concentrations by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Arcos-160 SOP, Spectro, NJ). Soil pH was determined in a 1:2 v:v (soil:water) mixture (Sikora and Kissel, 2014) and averaged 7.1 in 2012 and 7.3 in 2013.

Selected Mehlich-3 nutrient concentration means include 15 mg P kg⁻¹, 64 mg K kg⁻¹, 1643 mg Ca kg⁻¹, 302 mg Mg kg⁻¹, 8 mg S kg⁻¹, 228 mg Mn kg⁻¹, and 2.6 mg Zn kg⁻¹ in 2012 and 58 mg P kg⁻¹, 96 mg K kg⁻¹, 1762 mg Ca kg⁻¹, 287 mg Mg kg⁻¹, 11 mg S kg⁻¹, 152 mg Mn kg⁻¹, and 2.7 mg Zn kg⁻¹ in 2013. Soil organic matter content was determined using the weight loss-on-ignition method (Schulte and Hopkins, 1996) and averaged 22 g kg⁻¹ in 2012 and 23 g kg⁻¹ in 2013.

Experimental Design and Treatments

Each experiment was a randomized complete block design with four adjacent blocks that accommodated three, 10-m long strips of each soybean cultivar with each strip containing 20, 38-cm wide rows. Three glyphosate-resistant soybean cultivars belonging to a different MG were selected for this study and randomized within each block. The cultivars included Armor 39-R16

(Armor Seed LLC, Jonesboro, AR), Armor 48-R40, and Armor 53-R15 (2012) or Armor 55-R22 (2013) to represent cultivars that can be described as an indeterminate 3.9 maturity group (MG), an indeterminate 4.7 MG, and a determinate 5.3 (2012) or 5.5 (2013) MG, respectively. Each cultivar was planted into a conventionally tilled seedbed with a seeding rate of 417,600 seeds ha⁻¹. All cultivars contained the Roundup Ready 2 yield gene (Monsanto Co., St Louis, MO). The trials were planted on 22 May 2012 and 26 June 2013 and emerged on 29 May 2012 and 3 July 2013. The late planting date in 2013 was due to prior plantings having insufficient soybean populations caused by deer (*Odocoileus virginianus*) damage and soil crusting following untimely rain.

Crop Management

To ensure plant nutrition was not yield limiting, the 2012 trial was fertilized with 25 kg P ha⁻¹ as triple superphosphate (200 g P kg⁻¹); 55 kg K ha⁻¹ as muriate of potash (500 g K kg⁻¹); 18 kg K, 22 kg S, and 11 kg Mg ha⁻¹ as K₂SO₄·2MgSO₄ (180 g K, 215 g S, and 105 g Mg kg⁻¹); and 0.56 kg B ha⁻¹ as Na₂B₈O₁₃·4H₂O (205 g B kg⁻¹, Rio Tinto Minerals, Greenwood Village, CO). The 2013 trial was fertilized with 70 kg K ha⁻¹ as muriate of potash and 0.56 kg B ha⁻¹. Both research areas were flood-irrigated as needed, and irrigation and pest management were done following University of Arkansas Cooperative Extension Service recommendations (University of Arkansas, 2000).

Plant Sampling and Analysis

After soybean emergence, eight (2012) to ten (2013), 1.2-m long areas were selected within the interior 14 rows of each plot and thinned to a uniform density of 15 plants 1.2 m⁻¹ of linear row (equivalent to 322,910 plants ha⁻¹) and used for plant sampling during the season. Plant samples were collected eight (2012) to ten (2013) times between the V5 and R8 (maturity)

stages (Table 4.1). At each sample time, the 15 whole plants were cut at the soil surface, bundled in a labeled paper bag, placed in an ice-filled cooler, and transported to a nearby lab for processing. The plants were cleansed to remove dust by a brief rinse in tap water followed by a second rinse in deionized water. Each plant was examined and the numbers of nodes and branches and the presence of flowers at each node were recorded to determine the average plant development stage. The plants were divided into trifoliolate leaves, petioles, stems, pods, and seeds. With the exception of the final two sample times in 2012 and the final four (MG 3.9 and 4.7) or five (MG 5.5) sample times in 2013, pods included seeds. For the final 2 to 5 sample times, the seeds were removed from the pods by hand allowing separate pod and seed weights to be recorded. Field seed yield was measured for each cultivar by harvesting 10 to 15 m² within each block with a small-plot combine. The weight and moisture of the harvested seed were determined and final yield was calculated based on a seed moisture content of 130 g H₂O kg⁻¹.

Plant samples were dried at 60°C in a forced-draft oven for 7 d, weighed for dry matter, and ground in a Wiley mill to <1 mm diameter particle size. A 0.250 ±0.005 g subsample was weighed, digested with concentrated HNO₃ and 30% H₂O₂ (Jones and Case, 1990), and the digests were analyzed by ICP-AES for K concentration. For the determination of seed-K concentration, seeds were stored in an air conditioned lab (21°C) for 30 d before being digested at which time moisture content was 80 (±10) g H₂O kg⁻¹. A subsample of four whole seeds was weighed, digested, and analyzed as previously described.

The K content of each plant part for each sample time was calculated as the product of K concentration and dry matter accumulation and expressed as kg K ha⁻¹. The percent distribution of total dry matter and K content among the individual plant structures was calculated for each sample time. The crop growth rate (CGR, kg dry matter ha⁻¹ d⁻¹) and K uptake rate (KUR, kg K

ha⁻¹ d⁻¹) during the growing season were calculated for every day (1 d intervals) using the aboveground dry matter and K content for each year and cultivar across time as predicted with the Gaussian model (Archontoulis and Miguez, 2015). The amounts of K uptake and K removal per unit (kg) of seed yield were calculated using actual data (i.e., rather than predicted) as the ratio of the maximum total aboveground-K uptake during the growing season and mature seed-K content, respectively, to the seed yield (Eq. 1 and 2).

$$\text{Eq. 1. K uptake} = \frac{\text{Maximum total aboveground K content during the growing season (g)}}{\text{Seed yield (kg)}}$$

$$\text{Eq. 2. K removal} = \frac{\text{Mature seed K content (g)}}{\text{Seed yield (kg)}}$$

Actual (Ac) and apparent (Ap) harvest index (HI) values were calculated for seed (AcHI and ApHI) and K (AcKHI and ApKHI) as outlined by Schapaugh and Wilcox (1980) using Equations 3-6. The ApHI and ApKHI were calculated four (MG 3.9 and 4.7) or five (MG 5.5) times between the R5.5 and R8 growth stages in 2013 [Eq. 7 and 8].

$$\text{Eq. 3. AcHI} = \frac{\text{Mature seed weight (kg)}}{\text{Maximum total aboveground dry matter during the growing season (kg)}}$$

$$\text{Eq. 4. ApHI} = \frac{\text{Mature seed weight (kg)}}{\text{Total aboveground dry matter at harvest (kg)}}$$

$$\text{Eq. 5. AcKHI} = \frac{\text{Mature seed K content (kg)}}{\text{Maximum total aboveground K content during the growing season (kg)}}$$

$$\text{Eq. 6. ApKHI} = \frac{\text{Mature seed K content (kg)}}{\text{Total aboveground K content at harvest (kg)}}$$

$$\text{Eq. 7. ApHI (at any growth stage)} = \frac{\text{Seed weight (kg)}}{\text{Total aboveground dry matter (kg)}}$$

$$\text{Eq. 8. ApKHI (at any growth stage)} = \frac{\text{Seed K content (kg)}}{\text{Total aboveground K content (kg)}}$$

The amount of dry matter and K mobilized from the aboveground plant structures to the developing seeds was calculated in 2013 as the change in the dry matter and K content from i) leaves and petioles from the R5.5 to R7 stages (before leaf and petiole drop, Eq. 9-10) and ii) stems and pods from the R5.5 to R8 stages (post leaf and petiole drop, Eq. 11-12) (Loberg et al., 1984). To account for the dry matter and K contained in the fallen leaves and petioles which were not collected between the R5.5 and 7.0 stages, the changes in leaf and petiole dry matter and K content were multiplied by the ApHI and ApKHI, respectively. We assumed that the change in dry matter and K content for leaves and petioles from stage R5.5 to R7 was the same proportion of dry matter and K represented by the ApHI and ApKHI, respectively, mobilized from the leaves and petioles to the seeds and rest of the dry matter and K was equivalent to the dry matter and K content of fallen leaves and petioles. Finally, the amounts of dry matter and K mobilized from individual plant structures to seeds were summed to calculate the total dry matter and K mobilization.

$$\begin{aligned} \text{Eq. 9. Dry matter mobilized from leaves and petioles} \\ = (\text{Dry matter content at R5.5} - \text{Dry matter content at R7}) \times \text{ApHI} \end{aligned}$$

$$\begin{aligned} \text{Eq. 10. Potassium mobilized from leaves and petioles} \\ = (\text{K content at R5.5} - \text{K content at R7}) \times \text{ApKHI} \end{aligned}$$

$$\begin{aligned} \text{Eq. 11. Dry matter mobilized from stem and pods} \\ = \text{Dry matter content at R5.5} - \text{Dry matter content at R8} \end{aligned}$$

$$\text{Eq. 12. Potassium mobilized from stems and pods} = \text{K content at R5.5} - \text{K content at R8}$$

The percent of dry matter and K mobilized from plant structures to seed was calculated as the ratio of the mobilized dry matter and K content of each individual plant part to the dry matter

and K content of that plant part at the R5.5 stage [Eq. 13]. The percent contribution of the seed dry matter and K content through mobilization by each plant part was also calculated as the ratio of the mobilized dry matter and K content of each individual plant part to the dry matter and K content of mature seeds, respectively [Eq. 14].

$$\text{Eq. 13. \% dry matter or K mobilized} = \frac{\text{Amount of dry matter or K mobilized (kg)}}{\text{Dry matter or K content at R5.5 stage (kg)}} \times 100$$

$$\begin{aligned} \text{Eq. 14. \% contribution of mobilized dry matter or K content to the mature seed} \\ = \frac{\text{Amount of dry matter or K mobilized (kg)}}{\text{Dry matter or K content of mature seeds (kg)}} \times 100 \end{aligned}$$

Statistical Analysis

Each site-year was a randomized complete block design that included three soybean cultivars (fixed effect) and four blocks (random effect). The data were analyzed by year because the initial ANOVA with year included as a fixed effect model term (main-plot using a split-plot treatment structure) showed that the year by cultivar interaction was statistically significant for most measured variables. The difference in planting dates and growth duration (Table 4.1) between years may have contributed to the significant year interaction. The primary interest of this research was to compare cultivars. Therefore, ANOVA was performed by year for all the variables.

Node accumulation across time (days after emergence, DAE) data were characterized with a linear-plateau model using the NLIN procedure of SAS (v9.4, SAS Inst., Cary, NC). A Gaussian model was used to characterize dry matter and K accumulation in the aboveground vegetative (leaves, petioles, and stems) and total plant structures (vegetative + pods including seeds) across time using JMP Pro (v12, SAS Inst., Cary, NC). The location from which plant samples were collected within each block was randomized for each cultivar. Replicate data were used for modeling each variable. In the Gaussian equation [$Y = A \times \text{Exp}(-0.5 \times ((X-B)/C)^2)$], the

coefficient 'A' is the peak value (kg dry matter ha⁻¹ or kg K ha⁻¹), coefficient 'B' is the critical point with units of DAE (e.g., the DAE number at which dry matter and K content peaked), and coefficient 'C' has units of DAE and represents the width of the bell-shaped Gaussian curve (Archontoulis and Miguez, 2015).

The predicted CGR and KUR of each cultivar was regressed against DAE by year using the GLM procedure in SAS. The model included the linear, quadratic, and cubic DAE terms and their interaction with cultivar. The percentage of aboveground dry matter and K content represented by each sampled plant part (leaves, petioles, stems, and pods including seeds) was regressed using replicate data against DAE by year with the MIXED procedure in SAS. The model included the linear and quadratic terms of DAE and their interaction with cultivar as fixed effects and block as random effect. Each GLM and MIXED models was refined by eliminating the most complex nonsignificant ($P>0.10$) model terms in a stepwise fashion until the simplest, model with significant terms was obtained. The percentage of aboveground dry matter and K content for each plant part was compared among cultivars at each reproductive stage using an ESTIMATE statement (rather than LSMEANS and DIFF statements) since the same reproductive stage for each cultivar occurred at different DAE (Table 4.1). The K concentration of each sampled plant part using replicate data from all sample times and 2013 ApHI and ApKHI data from the final four or five sample times was modeled across time using the same procedure.

Seed yield, aboveground-K content and seed-K content per unit (kg) of seed yield, AcHI, ApHI, AcKHI, and ApKHI at maturity, and the percentages of dry matter and K mobilization were analyzed by year using the MIXED procedure of SAS. When a significant F-test was obtained for any variable, Fisher's protected LSD at the 0.05 probability level was used to separate the means. The studentized residuals distribution and Cook's *D* statistic were examined

for each variable to identify possible outliers (studentized residual $> \pm 2.5$) and influential data ($D > \pm 0.5$), respectively. Three ApKHI values were identified as outliers and the model was refit by omitting the outliers.

RESULTS AND DISCUSSION

Plant Development

The plant developmental stages of each soybean cultivar are summarized in Table 4.2. The MG 3.9 cultivar matured 10 d before the MG 4.7 cultivar and 21-24 d before the MG 5.3/5.5 cultivar. The MG 3.9 cultivar flowered 4 to 7 d earlier than the MG 4.7 and 16 to 22 d earlier than the MG 5.3/5.5 cultivar. The flowering period (R1-2 stages, Fehr et al., 1971) of the determinate MG 5.3/5.5 cultivar lasted only 5 or 6 d compared to 12 to 21 d for the two indeterminate cultivars (MG 3.9 and 4.7), but both growth habits flowered up to the R4 stage. The length of the pod set period (R2-5) was comparable for all three cultivars within each year. However, the length of the seed-filling period (R5-7) for the indeterminate cultivars was 7 (2012) to 9 (2013) d shorter than the MG 5.3/5.5 cultivar. These results agree with the information reported by Egli and Leggett (1973), Beaver et al. (1985), and Zhang et al. (2004) regarding the growth habits exhibited by determinate and indeterminate cultivars and cultivars of different MG.

Soybean accumulated an average of 15 (2013) to 18 (2012) nodes for the MG 3.9, 17 (2013) to 20 (2012) nodes for the MG 4.7, and 14 (2012) to 16 (2013) nodes for the MG 5.3/5.5 cultivar. The linear-plateau model showed that node accumulation for the two indeterminate cultivars (MG 3.9 and 4.7) in both years peaked at the R5 stage (Fig. 4.1a, b). Node accumulation for the determinate cultivar peaked at the R3 stage in 2012 (MG 5.3) and at the R4 stage in 2013 (MG 5.5). Regardless of soybean MG, growth habit, and year, a new node was produced every 3 to 4 d until maximum node number was reached.

The determinate MG 5.3/5.5 cultivar was shorter, had fewer main-stem nodes, and more primary branches compared to the indeterminate MG 3.9 and 4.7 cultivars, which agrees with the growth generalizations of determinate and indeterminate soybean cultivars (Egli and Leggett, 1973; Beaver et al., 1985; Wilcox and Frankenberger, 1987). The determinate MG 5.3/5.5 cultivar continued to set nodes beyond the R1 stage. Bernard (1972) and Egli and Leggett (1973) both noted that determinate soybean cultivars may continue to increase in height or node number following flowering.

Dry Matter Accumulation

Total aboveground dry matter accumulation was rapid from the vegetative stage to the onset of the seed-filling period (R5) and declined as the leaves senesced (R7) and seed matured (Fig. 4.1c, d). In 2012, the predicted maximum dry matter accumulation for all three cultivars was similar, but, in 2013, the predicted aboveground maximum dry matter was different among the three cultivars (coefficient A, Table 4.3). The MG 5.5 cultivar had 21% greater aboveground dry matter than the MG 3.9 cultivar and 30% higher than MG 4.7 cultivar. Although we did not compare dry matter accumulation among cultivars at each reproductive stage, the amount of aboveground dry matter was numerically different among cultivars in both years. Soybean accumulated 18 (2013) to 19% (2012) of its maximum dry matter by full-bloom (R2) for the MG 3.9, 26 to 29% for the MG 4.7, and 32 to 36% for the MG 5.3/5.5. Dry matter accumulation during the period (about 10 d) between the full-pod (R4) and seed initiation (R5) stages was numerically greater in 2012 than 2013. Dry matter accumulation expressed as a percentage of the maximum dry matter accounted for 42 (2013) to 52% (2012) for the MG 3.9, 51 to 63% for the MG 4.7, and 51 to 69% for the MG 5.3/5.5 by the R4 stage and 66 to 67% for the MG 3.9, 62 to 88% for the MG 4.7, and 70 to 79% for the MG 5.3/5.5 by the R5 stage. Dry matter

accumulation peaked (100%) at the same growth stage, R6.0-6.5, for all three cultivars in both years. However, the time (coefficient B, Table 4.3) required for maximal aboveground dry matter accumulation increased as MG increased during both years. The dry matter accumulation for the MG 3.9 cultivar peaked 4 to 5 d earlier than the MG 4.7 and 13 to 16 d earlier than the MG 5.3/5.5 cultivar.

The aboveground dry matter accumulation pattern of these three cultivars was similar to that reported for MG III and IV cultivars by Egli and Leggett (1973), Kollman et al. (1974), and Beaver et al. (1985). The range of maximum aboveground dry matter accumulation for our cultivars (8.4-10.8 Mg ha⁻¹ dry matter with seed yields of 3.0-4.0 Mg ha⁻¹) was numerically greater than the range (4.7-6.2 Mg ha⁻¹ for 1.2-2.0 Mg ha⁻¹) reported by Borst and Thatcher (1931) and Hammond et al. (1951), similar with the range (8.6-9.8 Mg ha⁻¹ for 2.7-3.5 Mg ha⁻¹) reported by Hanway and Weber (1971a, 1971d) and Bender et al. (2015), and lower than the value (18.6 Mg ha⁻¹ for 6.8 Mg ha⁻¹) reported by Flannery (1986). The percent of dry matter accumulation after the R4 stage in our study (48-61%) was higher than the percentages (34-42%) reported by Hammond et al. (1951) and Hanway and Weber (1971b), but similar to that reported by Bender et al. (2015; 51%). Our study showed that maximum aboveground dry matter accumulation was growth stage specific (i.e. R6.0-6.5) and agrees with results reported by Egli and Leggett (1973) and Bender et al. (2015).

The magnitude of vegetative (leaf, petiole, and stem) dry matter accumulation and the DAE that peak vegetative dry matter occurred was affected by cultivar each year (Table 4.3; Fig. 4.1e-f). The maximum vegetative dry matter of the MG 5.3/5.5 cultivar was greater than dry matter produced by the MG 3.9 and 4.7 cultivars, ranging from 11 to 41% greater in 2012 and 36 to 39% greater in 2013 (coefficient A, Table 4.3). The MG 3.9 and 4.7 cultivars accumulated

similar vegetative dry matter amounts in 2013, but the maximal vegetative dry matter of the MG 4.7 cultivar was 27% greater than the MG 3.9 cultivar in 2012. Vegetative dry matter accumulation peaked at the R5.0-5.5 stage for each cultivar during both years (Table 4.1), ranging from 78 to 91 DAE in 2012 to 62 to 75 DAE in 2013 (coefficient B, Table 4.3). Egli and Leggett (1973) also reported maximal vegetative dry matter occurred during the early seed-filling period (R5-6).

The predicted CGR was a cubic function of DAE that was different for all three cultivars in both years (Table 4.4; Fig. 4.2a, b). The predicted maximum CGR was higher for the MG 3.9 and 4.7 cultivars (indeterminate) than the MG 5.3 (determinate) cultivar in 2012 (Fig. 4.2a) and the result was opposite in 2013 (Fig. 4.2b). Aboveground dry matter accumulated at maximum predicted rates of 214 kg ha⁻¹ d⁻¹ for MG 3.9, 190 kg ha⁻¹ d⁻¹ for MG 4.7, and 176 kg ha⁻¹ d⁻¹ for MG 5.3 soybean in 2012 and 163 kg ha⁻¹ d⁻¹ for MG 3.9, 142 kg ha⁻¹ d⁻¹ for MG 4.7, and 166 kg ha⁻¹ d⁻¹ for MG 5.5 soybean in 2013. The predicted maximum CGR occurred at the R4-5 stage for all three cultivars in both years, which corresponded to 67 to 72 DAE in 2012 and 53 to 61 DAE in 2013. The CGR between the R1 and R4 stages was higher for the MG 3.9 cultivar than the MG 5.3/5.5 cultivar (Fig. 4.2a, b) and close to 186 kg dry matter ha⁻¹ d⁻¹ reported by Hanway and Weber (1971b) for an indeterminate, MG II cultivar. Bender et al. (2015) also reported a maximum CGR of 151-175 kg ha⁻¹ d⁻¹ at the R4-5 stage for 2.8 and 3.4 MG cultivars.

Dry Matter Distribution

The percentage of aboveground dry matter represented by leaves, petioles, and stems was a quadratic function of DAE and by pods (including seeds) was a linear (2013) or quadratic (2012) function of DAE that was different among cultivars (Table 4.5; Fig. 4.3). The total aboveground dry matter distribution to leaves, petioles, and stems was similar for all three

cultivars during the first two sample times in both years except for petioles in 2013 which differed among cultivars from the earliest sample time (Fig. 4.3a-f). The proportion of the aboveground plant weight from leaves was maximal [58 (2013) to 64% (2012)] at the earliest sample time (V5-R1) and declined rapidly with increasing plant development (Fig. 4.3a, b). The proportion of petiole (Fig. 4.3c, d) and stem (Fig. 4.3e, f) dry matter peaked at pod set (R3-4; 18-22% for petioles and 35-36% for stems) and declined thereafter. The maximum leaf [1802 (2013) to 2462 (2012) kg ha⁻¹], petiole (1053-1672 kg ha⁻¹), and stem (2230-3053 kg ha⁻¹) dry matter actually occurred at the R5.0-5.5 developmental stage, 70 (2013) to 86 (2012) DAE. The distribution of the aboveground dry matter to pods (including seeds) was different among cultivars from the first pod (overall third) sample time in both years and increased between the onset of the seed-filling period (R5) and physiological maturity (R7; Table 4.5; Fig. 4.3g, h).

The distribution of the aboveground dry matter for each plant structure (leaves, petioles, stems, and pods) was different among cultivars at each reproductive developmental stage except for the leaves at the R5 and R5.5 stages (Fig. 4.3). The aboveground dry matter distribution for each plant structure at each reproductive stage was not statistically compared between years, but the percentages between the two years were numerically comparable. At the R2 (blooming) stage, the aboveground matter was 44 to 52% leaves (MG 5.3/5.5 = MG 4.7 < MG 3.9), 16 to 20% petioles (MG 5.3/5.5 = MG 4.7 > MG 3.9), and 32 to 37% stems (MG 5.3/5.5 > MG 4.7 = MG 3.9). By the R5 stage (onset of seed formation), the percentage of aboveground dry matter represented by petioles was 17 to 20% (MG 5.3/5.5 = MG 4.7 > MG 3.9) and stems was 32 to 38% (MG 5.3/5.5 > MG 4.7 = MG 3.9) and both were numerically comparable to the percentages at the R2 stage. Compared to the R2 stage, the dry matter of leaves at the R5 stage had declined to 29% and was the same among cultivars. Pods including seed accounted for 14 to

22% of dry matter at R5 (MG 5.3/5.5 < MG 4.7 < MG 3.9) and the observed differences among cultivars is likely due to each cultivar being at a slightly different stage during R5, which may last up to 25 d. Egli and Leggett (1973) reported that maximum vegetative dry matter accumulation also occurred at R5 and was comprised of 34% leaves, 14% petioles, 37% stems, and 15% pods (including seeds). At the R6.5 stage, the time of maximum aboveground dry matter accumulation, plant dry matter was 9 to 14% leaves (MG 4.7 > MG 5.3/5.5 = MG 3.9), 7 to 9% petioles (MG 4.7 = MG 5.3/5.5 > MG 3.9), 22 to 27% stems (MG 5.5 > MG 4.7 = MG 3.9), and 54 to 62% pods (MG 3.9 > MG 4.7 = MG 5.3/5.5). Results suggest that dry matter declined rapidly from the vegetative structures during the seed-filling period (R5-7) and subsequently mobilized to the developing seeds.

Potassium Accumulation

Aboveground-K accumulation across time peaked near the R6 stage (Fig. 4.4a, b), the same approximate time that aboveground dry matter peaked (R6.0-6.5). Maximum aboveground-K content was similar among the three cultivars within each year (coefficient A, Table 4.3). Aboveground-K content averaged 131 kg K ha⁻¹ in 2012 and 130 kg K ha⁻¹ in 2013 and peaked at R5.5-6.0 for each cultivar during each year. The DAE when peak K uptake occurred was different between growth habits (coefficient B, Table 4.3; Fig. 4.4a, b). Peak K accumulation for the MG 3.9 and 4.7 (indeterminate) cultivars occurred at similar time and 13 to 18 d earlier than the MG 5.3/5.5 (determinate) cultivar. The percentage of aboveground-K accumulated by full-bloom (R2) increased with the increase of MG amounting to 29 (2012) to 31% (2013) for the MG 3.9, 39 to 41% for the MG 4.7, and 42 to 49% for the MG 5.3/5.5 cultivar. The percentage of the maximal aboveground-K content among the three cultivars had increased substantially by the R4 stage, ranging from 59 (2013) to 64% (2012) for the MG 3.9, 69 to 73% for the MG 4.7,

and 67 to 73% for the MG 5.3/5.5. Maximum K accumulation in our study was growth stage specific and occurred at the R5.5-6.0 for each cultivar, which is consistent with research reported by Hammond et al. (1951), Flannery (1986), Sadler et al. (1991), and Bender et al. (2015).

The amount of K in aboveground vegetative plant parts differed among cultivars in 2012, but not in 2013 (coefficient A, Table 4.3). The vegetative plant parts accounted for 67 to 97 kg K ha⁻¹ representing 57 to 71% of the maximal aboveground-K content accumulated during the season. The 3.9 MG cultivar accumulated 27 to 31% less K in vegetative structures than the 4.7 and 5.3 cultivars in 2012. In 2013, the differences were not statistically significant, but the 3.9 MG cultivar accumulated the lowest numerical amount of K in vegetative structures during the short growing season (e.g., due to late planting) when plant development rate was rapid and differences in plant growth stages among cultivars of different MG were less (Table 4.1). The more rapid rate of plant development in 2013 is evident in that peak accumulation of K in vegetative plant parts, which was different among cultivars in both years, occurred in fewer days in 2013 than 2012 (coefficient B, range of 10 vs. 15 d, Table 4.3). The number of DAE for peak K accumulation in vegetative parts increased as MG increased, but the growth stage was consistently at the R4-5 stage across cultivars and years. These results suggest that long-season cultivars may allocate more K via active uptake directly to the developing seed than short-season cultivars and rely less on mobilization of K from vegetative plant structures. The majority of K is taken up following the initiation of reproductive growth suggesting that K deficiency during early reproductive growth may have minimal effect on soybean yield if corrected in a timely manner. After the R4 stage, the proportion of the total-K accumulation (30-35%) in our study was within the range of 28 to 42% reported by Hammond et al. (1951), Hanway and Weber (1971d), and Bender et al. (2015). The K accumulation pattern during the growing season and

amount of K uptake were similar to what has been previously reported (Henderson and Kamprath, 1970; Hanway and Weber, 1971d; Harper, 1971; Sadler et al., 1991; Bender et al., 2015).

The predicted K uptake rate derived from K uptake curve was a cubic function of time that was different for all three cultivars in both years (Table 4.4; Fig. 4.2c, d). In 2012, the maximum K uptake rate for both the MG 3.9 and 4.7, indeterminate cultivars was similar (2.2 kg K ha⁻¹ d⁻¹) and higher than the MG 5.5, determinate cultivar (2.1 kg K ha⁻¹ d⁻¹; Fig. 4.2c). In 2013, the maximum K uptake rate increased as the duration of growing season (MG) decreased with average values of 2.6, 2.5, and 1.9 kg K ha⁻¹ d⁻¹ for the MG 3.9, 4.7, and 5.5 cultivars, respectively (Fig. 4.2d). The statistically different maximum K uptake rates among cultivars suggest the demand for K by short-season cultivars may be more rapid than that of long-season cultivars. Regardless of year, maturity group, or growth habit, the predicted maximum K uptake rate occurred at the R3-4 stage, 63 to 70 DAE in 2012 (Fig. 4.2c) and 44 to 51 DAE in 2013 (Fig. 4.2d). The maximum demand for K occurs during the R3-4 stage during pod development (Henderson and Kamprath, 1970; Flannery, 1986; Bender et al., 2015). The maximum K uptake rates in our experiments are slightly higher than the K uptake rates of 1.5 kg K ha⁻¹ d⁻¹ reported by Hanway and Weber (1971d; MG II) and similar (2013) or lower (2012) than the K uptake rate of 2.8 kg K ha⁻¹ d⁻¹ reported by Bender et al. (2015) for MG II and III cultivars. Our results coupled with information from the literature are not conclusive but provide strong evidence suggesting the peak K uptake rate is greater for cultivars with a shorter growing season. The higher K uptake rates by the short-season indeterminate cultivars (MG 3.9 and 4.7) during the flowering and pod set periods (R1-4) suggest that these cultivars could require higher soil K fertility or may be more susceptible to K deficiency. Although we could not find any information for soybean, short-season cotton (*Gossypium hirsutum* L.) cultivars are apparently more

susceptible to K deficiency and require more K to maximize lint yield than long-season cultivars (Oosterhuis et al., 1990; Tupper et al., 1996; Wright, 1999; Clement-Bailey and Gwathmey, 2007).

Potassium Distribution

The K distribution among plant parts during the growing season was a quadratic function of DAE except for leaf-K content in 2013, which was a linear function of DAE (Table 4.5; Fig. 4.5). The percentages of aboveground-K content represented by leaves, petioles, stems (including branches), and pods (including seeds) was different among cultivars at each reproductive developmental stage except for the leaves at the R5 and R5.5 stages (Table 4.1; Fig. 4.5). Since the aboveground-K distribution for each plant structure at each reproductive stage was numerically comparable between years, a summary of the K distribution among plant structures averaged across years is warranted.

Soybean leaves accounted for 42 to 49% (MG 3.9 = MG 4.7 > MG 5.3/5.5) of the aboveground-K content just before flowering (R0; plants had unopen flower clusters) and the percentage of K residing in the leaves decreased linearly (2013) or quadratically (2012) across time (Fig. 4.5a, b). The percentage of the aboveground-K in petioles (Fig. 4.5c, d) and stems (Fig. 4.5e, f) increased until the R2 stage (full-bloom) when each represented 24 to 27% (MG 4.7 > MG 3.9 = MG 5.3/5.5) and 36 to 39% (MG 5.3/5.5 > MG 4.7 = MG 3.9), respectively, of the K. The maximum leaf- (29 kg K ha⁻¹), petiole- (26 kg K ha⁻¹), and stem-K (32 kg K ha⁻¹) content peaked at the R4-5 stage, regardless of year and growth habit. At the time of maximum K uptake (R5.5), the distribution of aboveground-K content was 15 to 20% in leaves (MG 4.7 > MG 3.9 = MG 5.3/5.5), 17% in petioles, 19 to 26% in stems (MG 5.3/5.5 > MG 3.9 = MG 4.7), and 46 to 53% in pods (MG 3.9 > MG 4.7 > MG 5.3/5.5). By R6.5, aboveground dry matter peaked, but the relative differences in aboveground-K distribution among cultivars had not changed. The

percentages of K in vegetative structures at R6.5 had declined to 7 to 17% in leaves, 4 to 7% in petioles, and 8 to 13% in stems while pod-K content represented 63 to 81% of the aboveground-K. The depletion of K in the leaves, petioles, and stems during seed-filling period (R5-7) indicates that a significant amount of K stored in the vegetative structures was translocated to the developing seeds. We could find no research that has characterized the season-long distribution of aboveground-K among plant parts of soybean. Hammond et al. (1951; indeterminate cultivar) reported that stems plus roots, leaves, pods, and seeds contained 5, 6, 17, and 72%, respectively, of the total-K content at maturity. Sadler et al. (1991, determinate cultivar) reported that the aboveground-K content at maturity was 17% leaves plus petioles, 17% stems, and 66% pods plus seeds.

Potassium Concentration

The change in leaf-K concentration during the growing season was a nonlinear function of time for each cultivar in both years (Table 4.6; Fig. 4.6a, b). For all cultivars except the MG 4.7 cultivar in 2013, the leaf-K concentration was constant and at its greatest concentration from the V5 to R1 stages and then it declined with plant development (Table 4.6). During both years, the leaf-K concentration for the MG 4.7 cultivar changed the least of the three cultivars with time and showed the lowest R^2 value. Reasons for the relatively poor relationship for the MG 4.7 cultivar are not known. Petiole-K concentration was greatest on the first sample time during both years and declined linearly across time with the rate of decline depending on cultivar (Table 4.6; Fig. 4.6c, d). The stem-K concentration was also a nonlinear function of time that differed among cultivars in 2012, but not in 2013 (Table 4.6; Fig. 4.6e, f). Stem-K concentrations were relatively constant from V5 to R2 in 2012. In 2013, the plateau in stem-K concentration was not evident in the model, but K concentrations for each of the first two sample times (V6-R2) were numerically comparable for each cultivar before they started to decline on the third sample time.

The numeric difference between years may be due to the later planting date and more rapid growth rate in 2013 (Fig. 4.2a, b). The pod-K (including seed) concentration change was different among cultivars in 2012, but the same in 2013 (Table 4.6; Fig. 4.6g, h). In both years, pod-K concentration peaked at the onset of pod formation (R3) and declined quadratically or linearly (MG 3.9 and MG 5.3 in 2012) with increasing plant age (Table 4.6).

The K concentration changes in the leaves, petioles, and stems across the growing season compared favorably with the results reported by Hanway and Weber (1971c) and Sojka et al. (1985). The K concentration decrease was due to dilution by increasing dry matter accumulation between the V5 and R5 stages, translocation of K among plant structures, and competition for K with the developing seed starting around the R5.5 stage (Henderson and Kamprath, 1970; Harper, 1971; Hanway and Weber, 1971c; Sale and Campbell, 1980; Loberg et al., 1984; Sojka et al., 1985). Although the K concentrations among plant structures were not statistically compared, the greater numerical K concentrations in the petioles than in the leaves and stems early in the growing season suggests that petioles may be an equally good or better tissue than trifoliolate leaves to assess K nutrition. The linear decline along with a greater range of petiole-K concentrations across the growing season may be advantageous for defining critical K concentrations for multiple growth stages. Although the literature does not contain any conclusive information for soybean, cotton petiole-K concentration of the uppermost fully-expanded leaf at peak bloom is correlated ($R^2 = 0.53-0.61$) with seed-cotton yield (Cassman et al., 1989). Hanway and Weber (1971c; indeterminate cultivars) and Sojka et al. (1985; determinate cultivar) also documented greater K concentrations in the petioles than in the leaves and stems early in the growing season. They also reported pod-K concentration initially

increased, but eventually decreased beginning at the onset of seed formation due to the mobilization of K from pods to seeds.

Seed Yield and Harvest Index

Soybean seed yield was statistically similar among cultivars within each year averaging 3953 kg ha⁻¹ in 2012 and 2968 kg ha⁻¹ in 2013 (Table 4.7). The numerically lower yields produced in 2013 were likely due to the late planting date, a direct result of untimely and substantial rain events that caused stand failures from two prior plantings. There was no trend for substantial yield benefits from the earlier or later maturing cultivars in either year. Scientists have postulated that the simultaneous vegetative and reproductive growth of cultivars having an indeterminate growth habit may be detrimental to pod set and grain yield due to competition for assimilates between vegetative and reproductive sinks (Hicks and Pendleton, 1969; Egli and Leggett, 1973; Tanner and Ahmed, 1974). Egli and Leggett (1973) argued that indeterminate cultivars may compensate for yield loss from assimilate competition between the vegetative and reproductive sinks by producing more assimilate during their longer flowering and pod set period (R1-4). For this reason, Bernard and Weiss (1973) suggested that cultivars possessing the indeterminate growth habit could have a yield advantage over determinate growth habit cultivars in low yield environments. However, numerous researchers have proposed that there is no consistent yield difference between determinate and indeterminate soybean from MG III and IV (Egli and Leggett, 1973; Beaver and Johnson, 1981; Beaver et al., 1985).

Neither the amount of K uptake nor the amount of K removed per unit (kg) of seed yield was influenced by soybean cultivar in either year (Table 4.7). Averaged across cultivars, soybean accumulated 33.8 (2012) to 44.6 (2013) g K kg⁻¹ seed and removed 19.6 (2012) to 23.1 (2013) g K kg⁻¹ seed, which is reasonably close to the K uptake (40.8 g K kg⁻¹ seed) and removal (18.4 g

K kg⁻¹ seed) values reported by Bender et al. (2015). Flannery (1986) reported that high-yielding soybean (6.8 Mg ha⁻¹) accumulated 59.3 g K and removed 28 g K kg⁻¹ seed yield.

The AcHI was similar among cultivars during each year with the harvested soybean seed accounting for an average of 45 (2012) and 49% (2013) of the maximum aboveground dry matter produced at the R6.0-6.5 stage (Table 4.7). In contrast, the ApHI was significantly affected by cultivar each year (Table 4.7). The MG 3.9 cultivar had the greatest ApHI each year, but the lowest ApHI was for the MG 4.7 cultivar in 2012 and the MG 5.5 cultivar in 2013. Soybean ApHI increased linearly from the onset of seed formation (R5) to maturity (R8) for all three cultivars at rates ranging from 0.95 to 1.31% d⁻¹ in 2013 (Fig. 4.7a). The ApHI was, on average, 7% and 10% greater than the AcHI in 2012 and 2013, respectively.

The AcKHI among cultivars was similar within each year with mean AcKHI values of 60% in 2012 and 52% in 2013 (Table 4.7). The ApKHI was not affected by cultivar in 2012 with a mean of 75%. In 2013, the MG 3.9 and 4.7 cultivars had equal ApKHI that were each greater than the MG 5.5 cultivar. Despite the differences among cultivars in final ApKHI, the ApKHI increased at a uniform rate (1.38% d⁻¹) among cultivars from the onset of seed development through maturity (Fig. 4.7b).

Limited information is available in the literature regarding AcHI and AcKHI. The range of AcHI (45-49%) and AcKHI (52-60%) of our two trials was higher than the AcHI (36-38%) and AcKHI (45-48%) reported by Bender et al. (2015), but close to the AcHI (39-45%) reported by Schapaugh and Wilcox (1980). The ApHI of soybean reported in the literature ranges from 45 to 59% (Beaver and Cooper, 1982; Beaver et al., 1985) and ApKHI ranges from 70 to 72% (Hammond et al., 1951; Hanway and Weber, 1971d). Schapaugh and Wilcox (1980) reported that AcHI and ApHI were highly correlated ($R^2 = 0.93-0.96$) and ApHI was 10-14% higher than

AcHI. They also showed that the seed harvest indices were neither influenced by soybean growth habit nor consistently correlated with soybean yield. Our replicated data revealed that AcKHI was positively correlated with seed yield [Yield (kg ha⁻¹) = 1989 + (40.42 × AcKHI); R² = 0.75] and seed-K content [Seed-K (kg ha⁻¹) = 25.7 + (0.824 × AcKHI); R² = 0.68] at harvest and negatively correlated with total-K uptake during the growing season [R^{5.5-6.0}; K uptake (kg ha⁻¹) = 179.6 – (0.882 × AcKHI); R² = 0.41, not shown].

Dry Matter and Potassium Mobilization

Dry matter changes among plant structures was used to estimate dry matter mobilization from the leaves, petioles, stems, and pods to the developing seeds using the 2013 data. Soybean plants mobilized an average of 26.5% of the aboveground vegetative dry matter to the developing seeds with average contributions of 10.9% from leaves, 6.8% from stems, 4.4% from pods, and 4.3% from petioles. The mobilization of dry matter from leaves and petioles differed among cultivars (Table 4.8). The amount of dry matter mobilized from leaves was similar for the MG 3.9 and 4.7 (indeterminate) cultivars, but 2.3 to 4.1% higher than the MG 5.5 (determinate) cultivar. The MG 4.7 cultivar mobilized 1.6% more dry matter from petioles compared to the MG 3.9 and the amount was intermediate for the MG 5.5. Regardless of cultivar, the total mobilized dry matter contributed an average of 48.6% of the mature seed weight with contributions in decreasing order from the leaves (18.4%), stems (13.2%), pods (9.4%), and petioles (7.6%). Hume and Criswell (1973) showed that soybean mobilized 21-25% of the ¹⁴C assimilated during the entire growing season to the seeds, which is reasonably close to our estimate (26.5%).

Averaged across cultivars, soybean plants mobilized an estimated 45.2% of the total vegetative K content to the developing seeds, which included an average of 14.6% from leaves,

8.0% from petioles, 12.1% from stems, and 10.8% from pods (Table 4.8). Significant differences among cultivars occurred only for K mobilization from leaves with the MG 4.7 cultivar mobilizing 3.3 to 3.9% more K than the MG 3.9 and MG 5.5 cultivars. Regardless of MG, the total-K mobilized from vegetative structures was equivalent to 69% of the seed-K content at maturity where the contribution was estimated to be 21.7% from leaves, 18.6% from stems, 16.5% from pods, and 12.2% from petioles.

Soybean seeds accumulate K from active root uptake during seed development and from translocation of K among plant structures (Hanway and Weber, 1971d). Potassium translocation from leaves, petioles, stems, and pods to seeds starts during the seed-filling period and continues through the R5.5 stage (Karlen et al., 1982; Loberg et al., 1984). The contribution of the total-K mobilized to the total seed-K content estimated in our study (69%) was within the 56 to 78% range that is reported in the literature (Hammond et al., 1951; Hanway and Weber, 1971d) and highlights the importance of the vegetative organs, especially the leaves (Hanway and Weber, 1971d), as the primary K source for the developing seed. Loberg et al. (1984; 23.6%) provided a similar estimate of seed-K content that was mobilized from soybean leaves.

CONCLUSIONS

Our experiment compared dry matter and K accumulation and yield of three soybean cultivars representing 3.9 (indeterminate), 4.7 (indeterminate) and 5.3/5.5 (determinate) MG grown under the same field conditions. Potassium accumulation and aboveground dry matter accumulation for all three cultivars peaked at a specific growth stages with maximal K accumulation occurring at the R5.5-6.0 stage and dry matter at the R6.0-6.5 stage, which led us to accept our first and second hypothesis, respectively. The MG 3.9 and 4.7 cultivars had higher K accumulation rates than the MG 5.5 cultivar during the early reproductive stages (R1-4). The

differences in K accumulation rates among cultivars did not affect K partitioning and the percentage of K mobilized to the developing seeds, suggesting that our third hypothesis should be rejected. The patterns of dry matter and K accumulation and partitioning suggest that K deficiency of soybean could possibly be corrected by timely fertilization during early reproductive growth with little or no yield loss. The petiole-K concentration was highest among vegetative structures early in the growing season and declined linearly with plant development suggesting that petioles might be a good tissue for monitoring the K nutritional status of soybean during the growing season.

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Table 4.1. The date, days after emergence (DAE), and growth stage that plant samples were collected in research trials conducted at the Pine Tree Research Station in 2012 and 2013.

Sample time	Sample date	DAE	Growth stage†‡		
			Armor 39-R16	Armor 48-R40	Armor 53-R15/55-R22§
<u>2012</u>					
1	26 June	28	R1	R0	V5
2	11 July	43	R2	R2	R0
3	24 July	56	R3	R2	R2
4	7 Aug.	70	R5	R4	R3
5	22 Aug.	85	R5.5	R5	R5
6	5 Sep.	99	R6	R5.5	R5.5
7	12 Sep.	106	R7	-	-
	19 Sep.	113	-	R6.5	-
	3 Oct.	127	-	-	R7
8	23 Sep.	117	R8	-	-
	3 Oct.	127	-	R8	-
	17 Oct.	141	-	-	R8
<u>2013</u>					
1	25 July	22	R1	V6	V6
2	6 Aug.	34	R3	R2	V9
3	15 Aug.	43	R4	R3	R2
4	27 Aug.	55	R5	R5	R4
5	7 Sep.	66	R5.5	R5.5	R5
6	18 Sep.	77	R6	R5.5	R5.5
7	28 Sep.	87	R7	R6.5	R5.5
8	8 Oct.	97	R8	R7.5	R6.5
9	18 Oct.	107	-	R8	R7
10	29 Oct.	118	-	-	R8

† Growth stage key: Fehr et al. (1971).

‡ Additional growth stages (not defined by Fehr et al., 1971): R0, Plants had flower clusters, but the flowers were not open; R5.5, areas of pod cavities at one of the top four nodes were 50% filled by developing seeds; and R6.5 and R7.5, one-half of plants in the growth stage above and one-half of plants in the growth stage below the listed value.

§ A MG 5.3 cultivar (Armor 53-R15) was used in 2012 and a MG 5.5 cultivar (Armor 55-R22) was used in 2013.

Table 4.2. The duration of plant developmental stages of three different maturity group (MG) soybean cultivars during the growing season in the research trials conducted at the Pine Tree Research Station in 2012 and 2013.

Cultivar MG	Season (E†-R8)	Vegetative period (E-R1)	Flowering period (R1-R2)	Pod set period (R2-R5)	Seed-filling period (R5-R7)	Reproductive period (R1-R8)
-----d-----						
<u>2012</u>						
MG 3.9	117	28	15	27	36	89
MG 4.7	127	35	21	29	35	92
MG 5.3	141	50	6	29	42	91
<u>2013</u>						
MG 3.9	97	22	12	21	32	75
MG 4.7	107	26	17	21	32	81
MG 5.5	118	38	5	23	41	80

† E, emergence.

Table 4.3. Coefficient and estimated parameter values for the Gaussian model for predicting dry matter and K accumulation in the aboveground vegetative (leaf, petiole, and stem) and total (vegetative + pods including seeds) plant structures of three different maturity group (MG) soybean cultivars during the growing season in the research trials conducted at the Pine Tree Research Station during 2012 and 2013.

Cultivar MG	Gaussian model† coefficients							
	2012				2013			
	A	B	C	R ²	A	B	C	R ²
	<u>Aboveground dry matter accumulation</u>							
MG 3.9	10318 a‡	96 c	28.6 b	0.95	8000 b	82 c	29.2 a	0.96
MG 4.7	10475 a	101 b	32.7 b	0.92	7461 c	86 b	31.3 a	0.96
MG 5.3/5.5§	11572 a	112 a	39.0 a	0.90	9679 a	95 a	34.7 a	0.94
	<u>Dry matter accumulation in vegetative plant parts</u>							
MG 3.9	5772 c	78 c	25.2 a	0.89	4329 b	62 b	23.9 a	0.92
MG 4.7	7316 b	85 b	26.9 a	0.88	4421 b	67 b	25.7 a	0.93
MG 5.3/5.5	8124 a	91 a	31.2 a	0.87	6029 a	75 a	28.6 a	0.91
	<u>Aboveground-K accumulation</u>							
MG 3.9	117 a	93 b	31.9 a	0.84	132 a	74 b	30.3 a	0.86
MG 4.7	129 a	98 b	34.5 a	0.78	129 a	76 b	32.7 a	0.79
MG 5.3/5.5	148 a	111 a	41.7 a	0.79	129 a	90 a	40.5 a	0.80
	<u>K accumulation in vegetative plant parts</u>							
MG 3.9	67 b	64 c	18.8 a	0.79	83 a	53 c	20.7 a	0.86
MG 4.7	92 a	75 b	22.1 a	0.85	90 a	58 b	23.7 a	0.82
MG 5.3/5.5	97 a	79 a	26.6 a	0.78	90 a	63 a	25.7 a	0.80

† In Gaussian model [$Y = A \times \text{Exp}(-0.5 \times ((X-B)/C)^2)$], the coefficient ‘A’ is the peak value (kg dry matter or K ha⁻¹), ‘B’ is the critical point (DAE), and ‘C’ is the value (DAE) that controls the width of the bell-shaped Gaussian curve.

‡ Similar letters in a column under each variable do not differ significantly at the 0.05 probability level.

§ A MG 5.3 cultivar was used in 2012 and a MG 5.5 cultivar was used in 2013.

Table 4.4. Coefficients of the polynomial model for predicting total crop growth rate and K uptake rate of three different maturity group (MG) soybean cultivars during the growing season in the research trials conducted at the Pine Tree Research Station during 2012 and 2013.

Cultivar MG	Polynomial model† coefficients									
	2012					2013				
	Intercept	Linear	Quadratic	Cubic	R^2	Intercept	Linear	Quadratic	Cubic	R^2
	<u>Crop growth rate</u>									
MG 3.9	55.91	-7.3271	0.3198	-0.00262	0.99	-50.38	4.0485	0.0769	-0.00146	0.99
MG 4.7	-3.91‡	-1.5565	0.1668	-0.00150	0.99	-40.87	3.7607	0.0470	-0.00100	0.99
MG 5.3/5.5§	-29.56	1.6320	0.0708	-0.00075	0.99	-23.98	2.5682	0.0694	-0.00099	0.99
	<u>K uptake rate</u>									
MG 3.9	-0.804	0.0400	0.00108	-0.000015	0.99	-1.219	0.1554	-0.00106	-0.000011	0.99
MG 4.7	-0.834	0.0500	0.00072	-0.000012	0.99	-1.033	0.1414	-0.00102	-0.000009	0.99
MG 5.3/5.5	-0.528	0.0451	0.00034	-0.000006	0.99	-0.277	0.0819	-0.00061	-0.000003	0.99

† Cubic model equation, $y = z + ax + bx^2 + cx^3$; where y, independent variable; x, days after emergence; z, intercept; a, linear coefficient; b, quadratic coefficient; and c, cubic coefficient.

‡ Coefficients are not significantly different from zero at the 0.10 probability level.

§ A MG 5.3 cultivar was used in 2012 and a MG 5.5 cultivar was used in 2013.

Table 4.5. Coefficients of the polynomial model for predicting the aboveground dry matter and K distribution for leaves, petioles, stems (including branches), and pods (including seed) of three different maturity group (MG) soybean cultivars during the growing season in research trials conducted at the Pine Tree Research Station during 2012 and 2013.

Cultivar MG	Polynomial model† coefficients							
	2012				2013			
	Intercept	Linear	Quadratic	R^2	Intercept	Linear	Quadratic	R^2
<u>Aboveground dry matter distribution</u>								
<u>Leaves</u>								
MG 3.9	92.36	-1.0788	0.0025	0.99	78.83	-0.9524	0.0013	0.99
MG 4.7	92.71	-1.1100	0.0037	0.99	74.57	-0.8176	0.0013	0.99
MG 5.3/5.5‡	81.80	-0.7191	0.0009	0.98	75.31	-0.7980	0.0013	0.98
<u>Petioles</u>								
MG 3.9	-2.53§	0.7253	-0.0061	0.81	-0.79§	0.7387	-0.0078	0.84
MG 4.7	-5.83	0.8283	-0.0061	0.74	1.12§	0.7387	-0.0075	0.82
MG 5.3/5.5	-10.27	0.9095	-0.0061	0.87	-2.09§	0.7387	-0.0065	0.93
<u>Stems</u>								
MG 3.9	12.75	0.6780	-0.0058	0.78	25.48	0.4678	-0.0062	0.77
MG 4.7	7.51	0.7916	-0.0058	0.81	23.86	0.5030	-0.0062	0.83
MG 5.3/5.5	4.02§	0.8910	-0.0058	0.80	19.25	0.6971	-0.0062	0.62
<u>Pods</u>								
MG 3.9	-89.29	1.7730	-0.0028§	0.99	-57.31	1.4413	NS#	0.99
MG 4.7	-185.08	3.6867	-0.0142	0.97	-54.86	1.2643	NS	0.98
MG 5.3/5.5	-53.68	0.5767§	0.0026§	0.98	-66.74	1.2428	NS	0.99
<u>Aboveground-K distribution</u>								
<u>Leaves</u>								
MG 3.9	93.52	-1.4009	0.0052	0.98	51.69	-0.5259	NS	0.90
MG 4.7	86.30	-1.1224	0.0043	0.94	47.68	-0.3495	NS	0.71
MG 5.3/5.5	76.53	-0.7629	0.0014	0.96	54.47	-0.4597	NS	0.86
<u>Petioles</u>								
MG 3.9	9.34	0.6042	-0.0067	0.73	5.20	0.9654	-0.0115	0.84
MG 4.7	5.50§	0.7221	-0.0067	0.74	6.49	0.9654	-0.0108	0.86
MG 5.3/5.5	-3.24§	0.8795	-0.0067	0.83	-1.84§	0.9654	-0.0089	0.93
<u>Stems</u>								
MG 3.9	11.70	0.8153	-0.0086	0.84	44.27	-0.0202§	-0.0047	0.86
MG 4.7	4.84§	0.9736	-0.0086	0.86	40.92	0.0541§	-0.0047	0.86
MG 5.3/5.5	1.05§	1.1241	-0.0086	0.77	41.00	0.1787§	-0.0047	0.81
<u>Pods</u>								
MG 3.9	-226.11	5.2719	-0.0215	0.99	-108.87	3.0935	-0.0108	0.99
MG 4.7	-253.00	5.0863	-0.0194	0.98	-44.42	0.8515	0.0043§	0.98
MG 5.3/5.5	-149.99	2.4517	-0.0047§	0.97	-108.99	2.2307	-0.0040§	0.99

† Linear model equation, $y = z + ax$ and quadratic model equation, $y = z + ax + bx^2$; where y, independent variable; x, days after emergence; z, intercept; a, linear coefficient; and b, quadratic coefficient.

‡ A MG 5.3 cultivar was used in 2012 and a MG 5.5 cultivar was used in 2013.

§ Coefficients are not significantly different from zero at the 0.10 probability level.

Quadratic coefficients are not significant at the 0.10 probability level.

Table 4.6. Coefficients of the polynomial model for predicting leaf-, petiole-, stem- (including branch), and pod- (including seed) K concentrations of three different maturity group (MG) soybean cultivars during the growing season in the research trials conducted at the Pine Tree Research Station during 2012 and 2013.

Cultivar MG	Polynomial model† coefficients							
	2012				2013			
	Intercept	Linear	Quadratic	R^2	Intercept	Linear	Quadratic	R^2
	<u>Leaf-K concentration</u>							
MG 3.9	13.75	0.0346‡	-0.0012	0.84	23.30	-0.2246	0.0015‡	0.46
MG 4.7	10.28	0.1303	-0.0012	0.31	24.65	-0.2275	0.0021	0.14
MG 5.3/5.5§	11.09	0.0957	-0.0012	0.80	16.65	0.0614‡	-0.0013	0.73
	<u>Petiole-K concentration</u>							
MG 3.9	35.77	-0.3228	NS#	0.79	59.52	-0.5315	NS	0.92
MG 4.7	31.71	-0.2414	NS	0.89	58.10	-0.4811	NS	0.82
MG 5.3/5.5	26.57	-0.1624	NS	0.67	40.28	-0.2911	NS	0.85
	<u>Stem-K concentration</u>							
MG 3.9	18.42	-0.0332‡	-0.0010	0.75	48.58	-0.7252	0.0030	0.89
MG 4.7	16.26	0.0182‡	-0.0010	0.78	50.56	-0.7252	0.0030	0.89
MG 5.3/5.5	15.14	0.0512‡	-0.0010	0.75	48.51	-0.7252	0.0030	0.89
	<u>Pod-K concentration</u>							
MG 3.9	29.34	-0.0972‡	-0.0003‡	0.76	55.64	-0.7500	0.0037	0.88
MG 4.7	91.89	-1.3012	0.0056	0.83	55.64	-0.7500	0.0037	0.88
MG 5.3/5.5	33.69	-0.1508‡	0.0002‡	0.62	55.64	-0.7500	0.0037	0.88

† Linear model equation, $y = z + ax$ and quadratic model equation, $y = z + ax + bx^2$; where y, independent variable; x, days after emergence; z, intercept; a, linear coefficient; and b, quadratic coefficient.

‡ Coefficients are not significantly different from zero at the 0.10 probability level.

§ A MG 5.3 cultivar was used in 2012 and a MG 5.5 cultivar was used in 2013.

Quadratic coefficients are not significant at the 0.10 probability level.

Table 4.7. Seed yield, K uptake and removal per unit of seed yield, actual (AcHI) and apparent (ApHI) harvest indices of seed, and actual (AcKHI) and apparent (ApKHI) harvest indices of K of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013.

Cultivar MG	Seed yield kg ha ⁻¹	K uptake g K kg ⁻¹ seed yield	K removal	AcHI	ApHI	AcKHI	ApKHI
				-----%-----			
				<u>2012</u>			
MG 3.9	3938	28.7	17.0	43	58	59	77
MG 4.7	3658	39.6	20.6	43	53	54	73
MG 5.3	4263	33.2	21.3	49	55	66	76
<i>P</i> -value	0.079	0.149	0.115	0.593	0.002	0.481	0.595
LSD(0.05)	ns†	ns	ns	ns	1.5	ns	ns
				<u>2013</u>			
MG 3.9	3069	43.9	22.2	52	62	51	71
MG 4.7	2814	46.8	22.8	50	61	50	72
MG 5.5	3021	43.2	24.2	46	54	56	65
<i>P</i> -value	0.473	0.610	0.772	0.398	0.003	0.743	0.049
LSD(0.05)	ns	ns	ns	ns	3.0	ns	5.4

† ns, not significant.

Table 4.8. Percent dry matter and K mobilization from aboveground plant structures to the seed of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2013.

Cultivar MG	Dry matter mobilization					K mobilization				
	Total	Leaf	Petiole	Stem	Pod	Total	Leaf	Petiole	Stem	Pod
	-----%-----									
MG 3.9	28.3	12.9	3.4	5.9	6.1	49.7	12.8	7.4	15.6	14.0
MG 4.7	25.2	11.1	5.0	5.5	3.6	43.0	16.7	7.5	10.4	8.4
MG 5.5	25.9	8.8	4.6	9.0	3.5	42.8	13.4	9.1	10.2	10.1
<i>P</i> -value	0.659	0.008	0.042	0.077	0.485	0.514	0.040	0.525	0.098	0.413
LSD(0.05)	ns†	1.9	1.3	ns	ns	ns	3.1	ns	ns	ns

† ns, not significant.

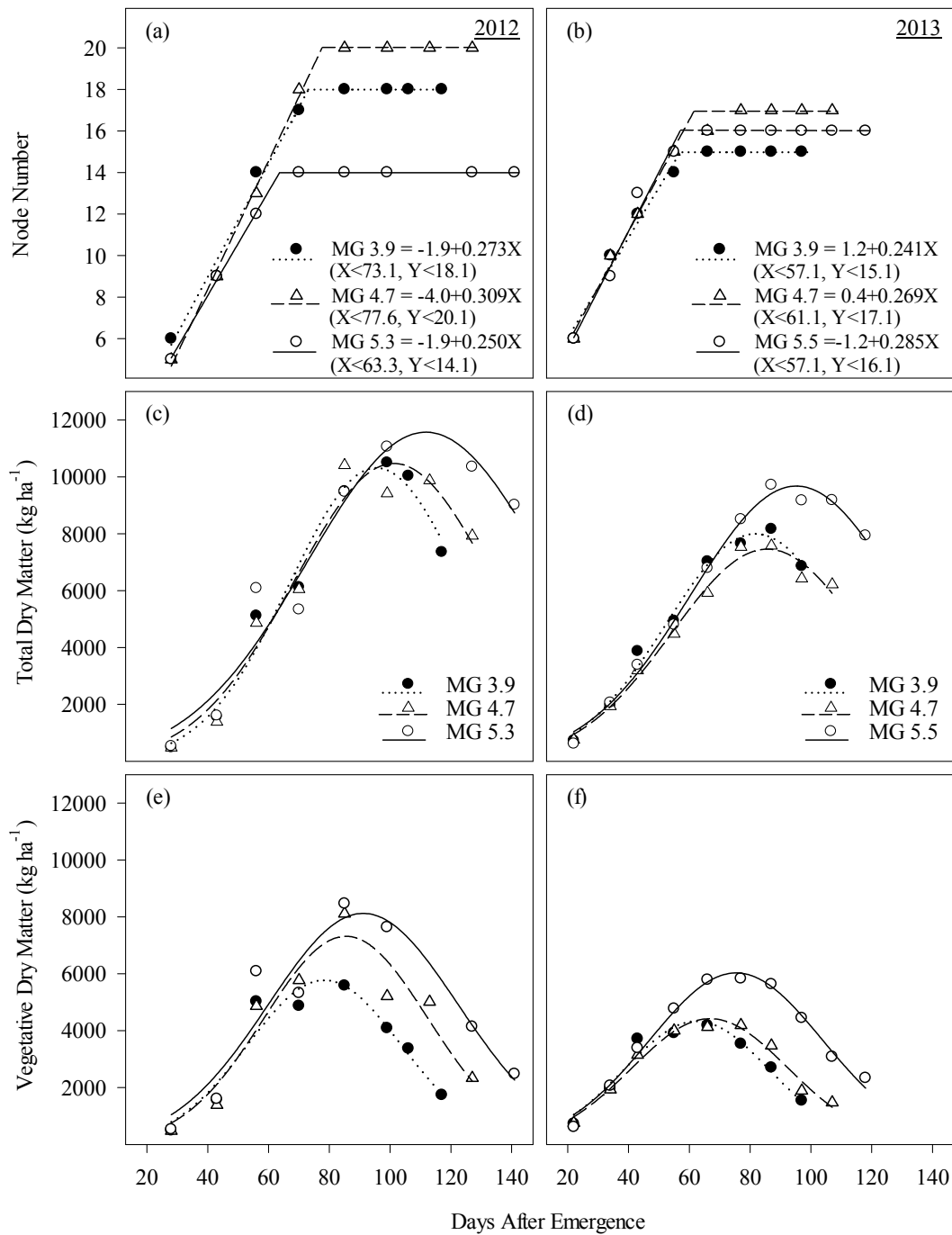


Fig. 4.1. Seasonal node (a-b), total dry matter (c-d), and vegetative dry matter (leaves, petioles, and stems; e-f) accumulation of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013. Node accumulation was predicted with a linear-plateau model. Aboveground total and vegetative dry matter accumulation were predicted with a Gaussian model. Coefficient and estimated parameter values of the Gaussian model are listed in Table 4.3. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

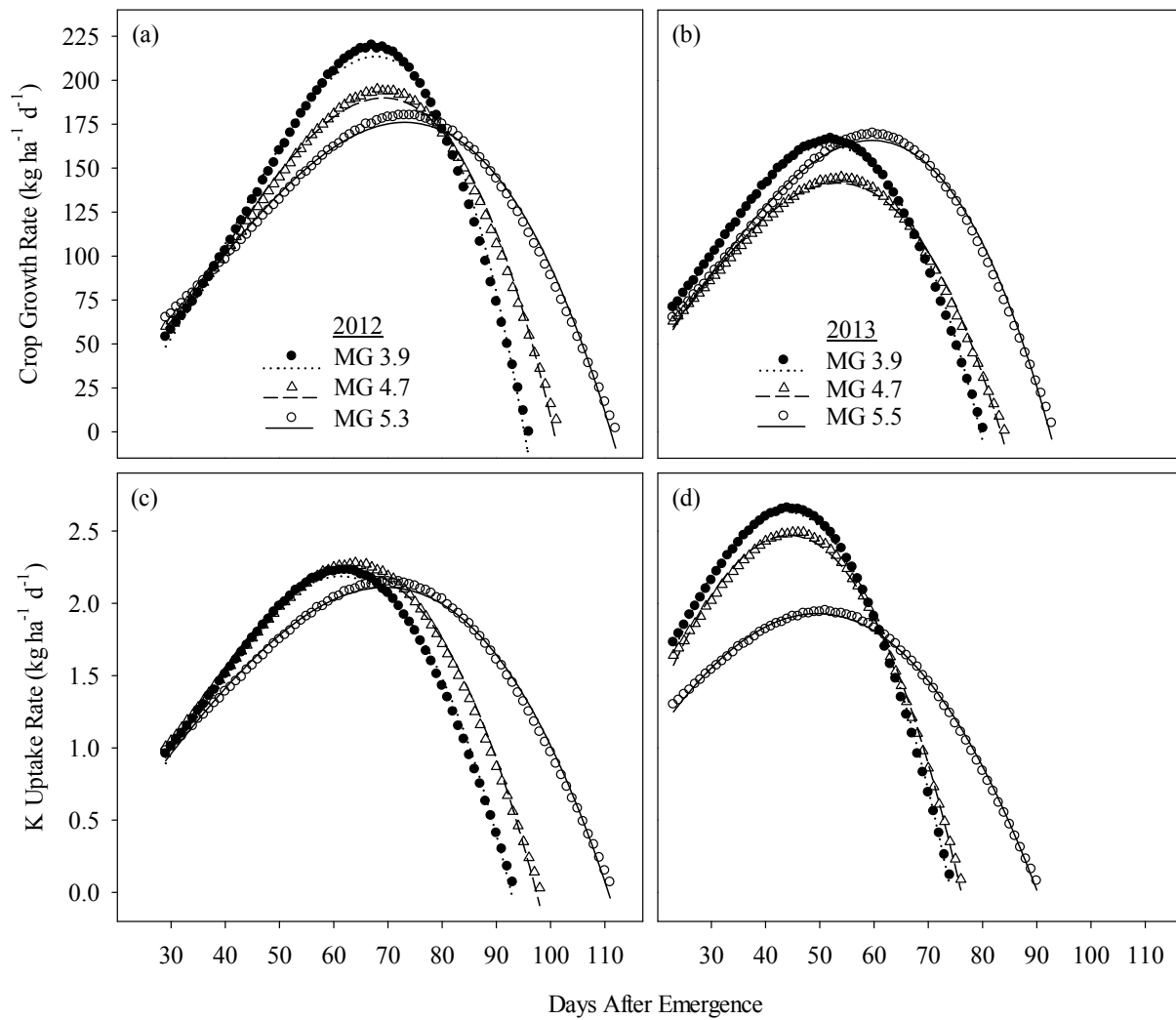


Fig. 4.2. Seasonal total crop growth rate (a-b) and K uptake rate (c-d) as predicted with a polynomial model of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013. Coefficient values are listed in Table 4.4. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

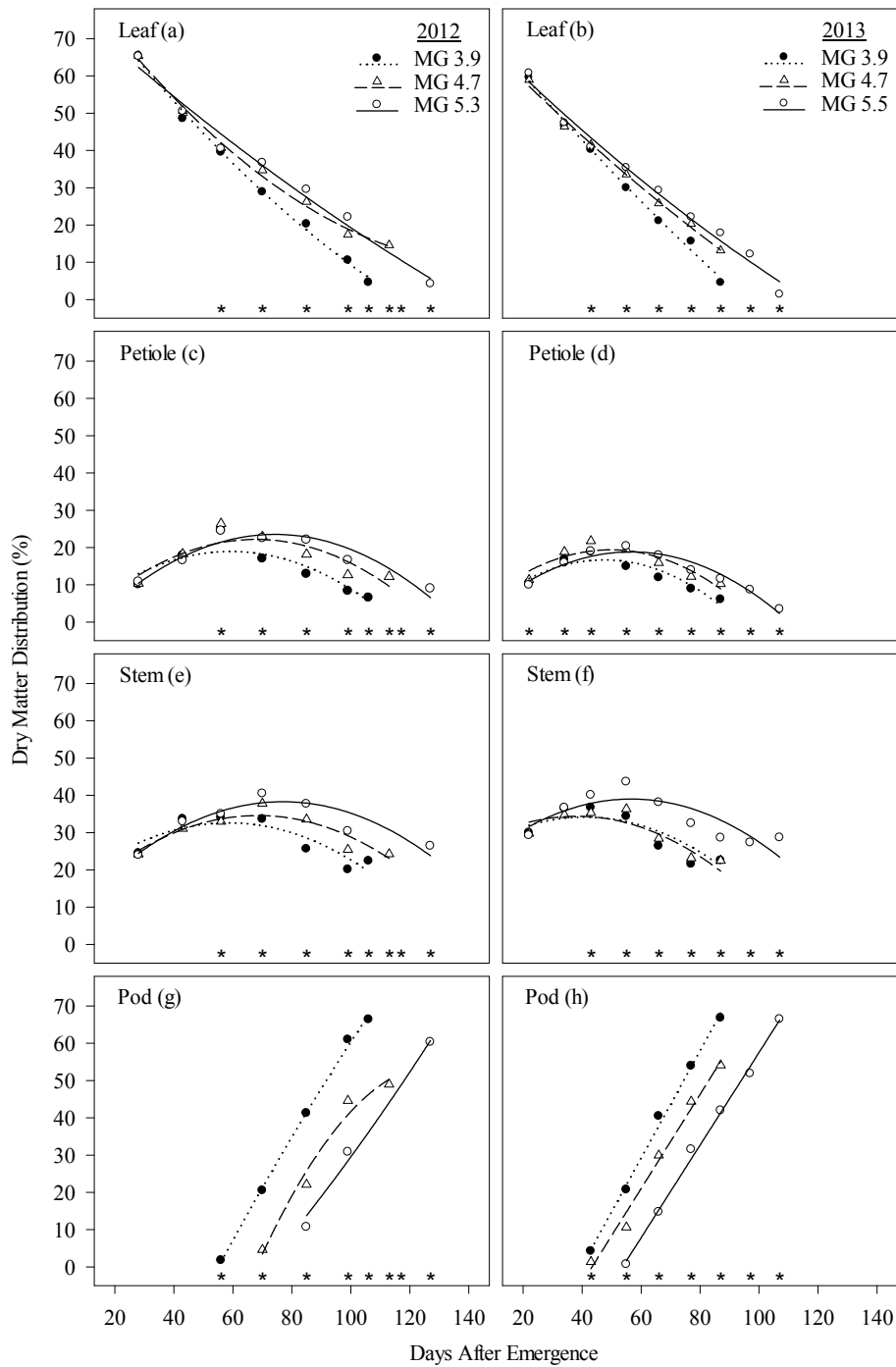


Fig. 4.3. Seasonal leaf (a-b), petiole (c-d), stem (including branch; e-f), and pod (including seed; f-g) dry matter distribution as predicted with a polynomial model of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013. An * represents the days after emergence that significant differences occur among cultivars for the predicted percent dry matter distribution at the 0.05 probability level. Coefficient values are listed in Table 4.5. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

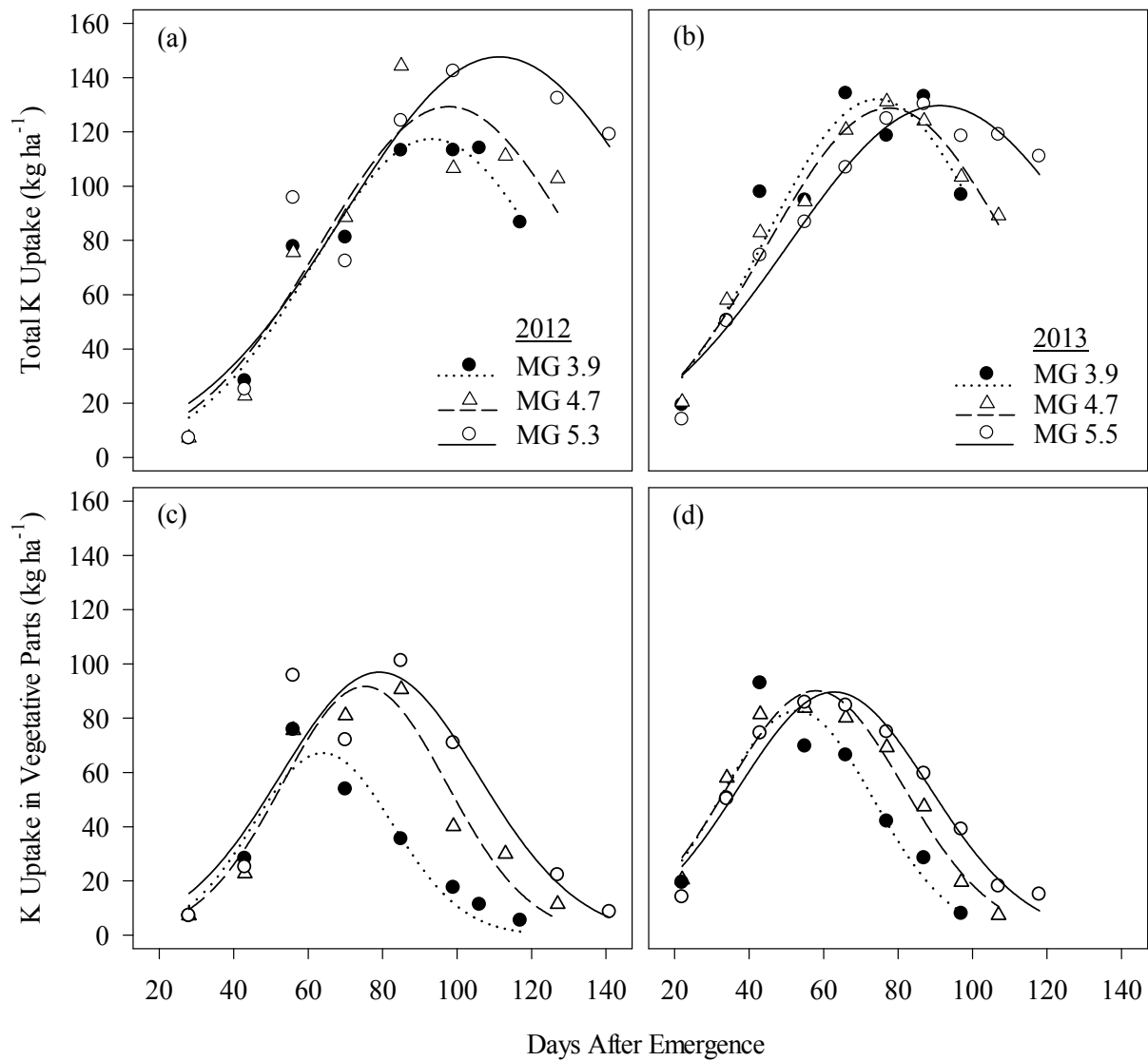


Fig. 4.4. Seasonal K uptake of aboveground plant parts (a-b) and vegetative plant parts (leaves, petioles, and stems; c-d) as predicted with a Gaussian model of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013. Coefficient and estimated parameter values are listed in Table 4.3. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

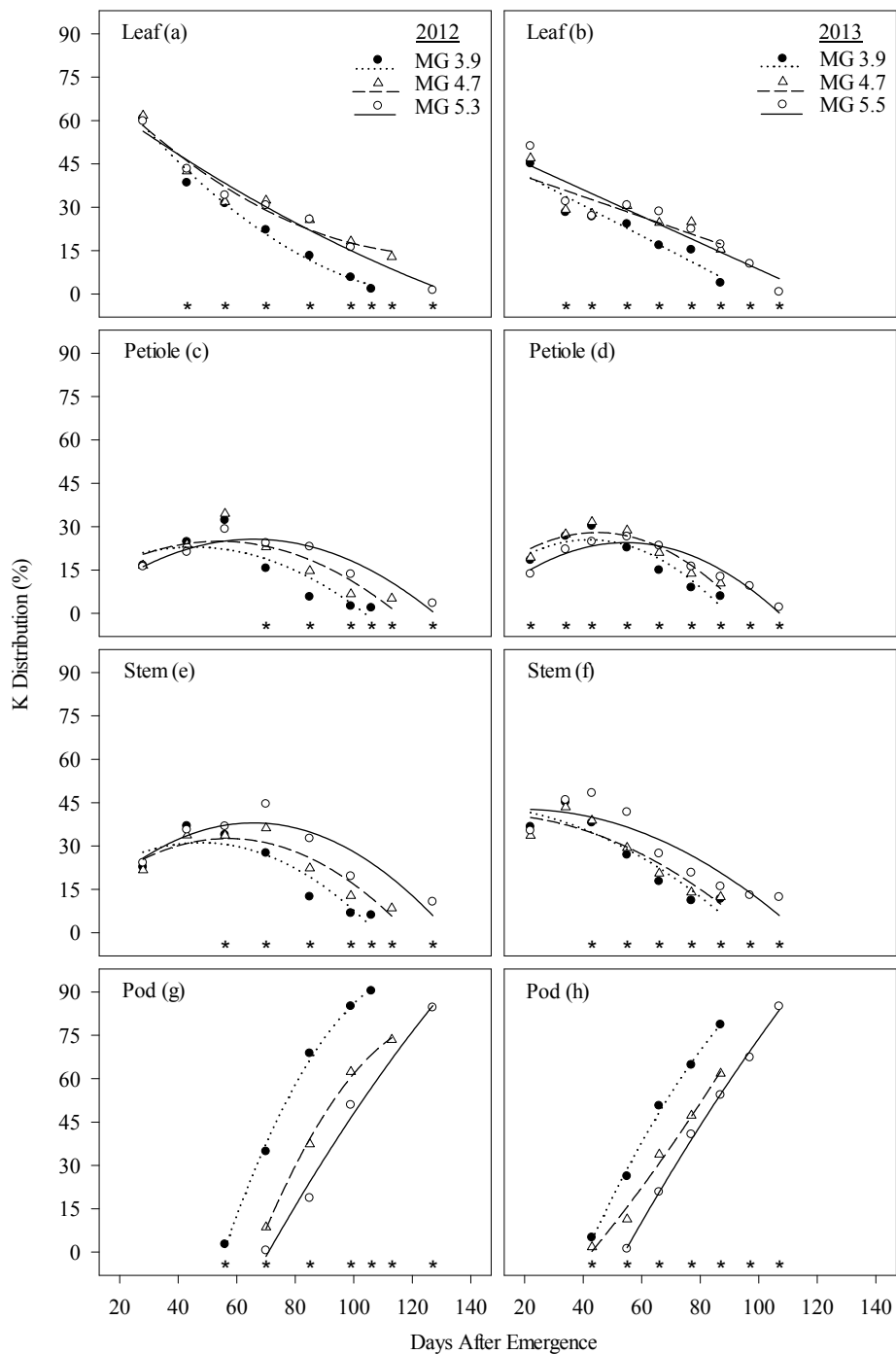


Fig. 4.5. Seasonal leaf- (a-b), petiole- (c-d), stem- (including branch; e-f), and pod- (including seed; g-h) K distribution as predicted with a polynomial model of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013. An * represents the days after emergence that significant differences occur among cultivars for the predicted percent K distribution at the 0.05 probability level. Coefficient values are listed in Table 4.5. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

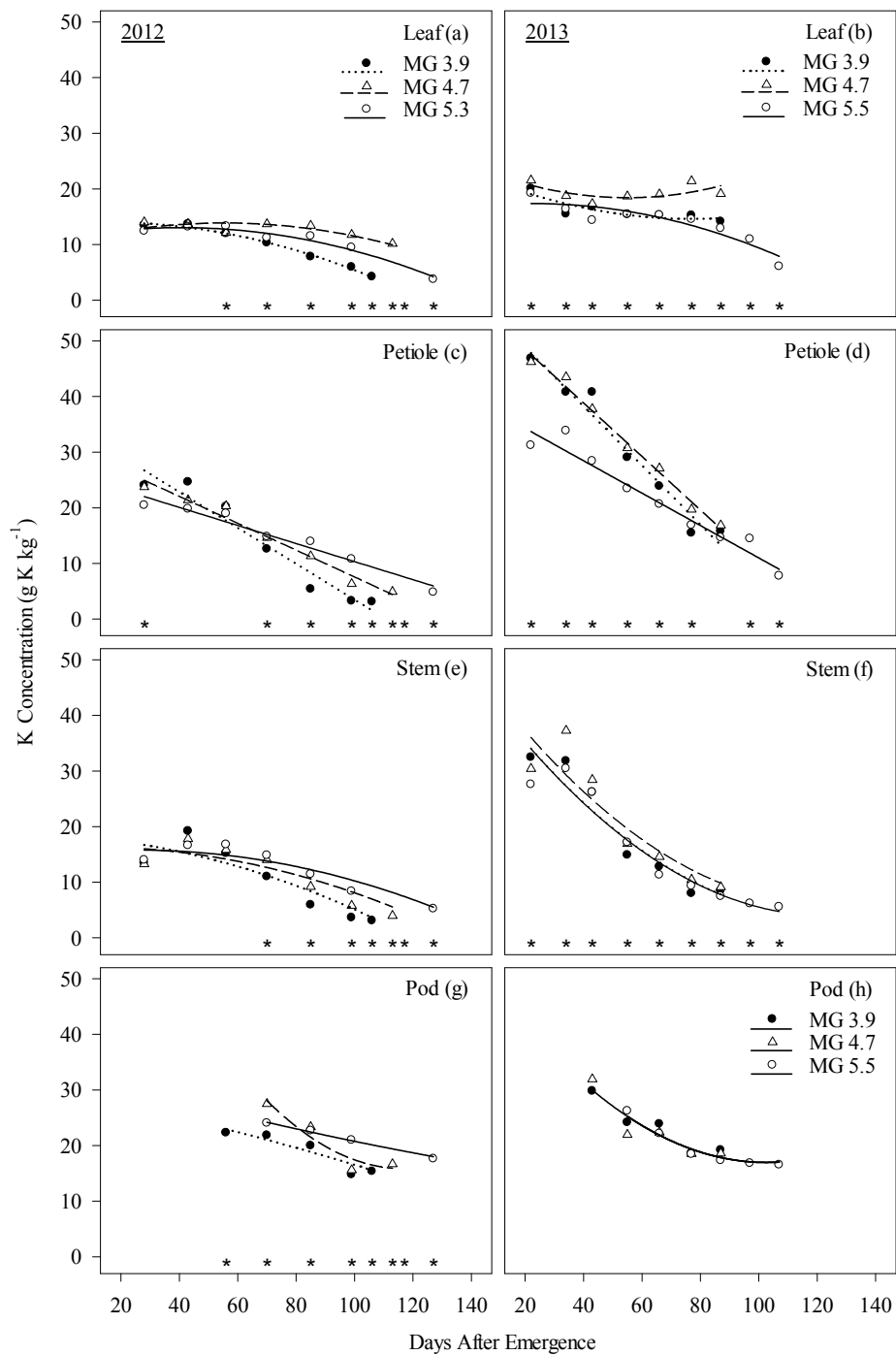


Fig. 4.6. Seasonal change of leaf- (a-b), petiole- (c-d), stem- (including branch; e-f), and pod- (including seed; g-h) K concentrations as predicted with a polynomial model of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2012 and 2013. An * represents the days after emergence that significant differences occur among cultivars of the predicted K concentrations at the 0.05 probability level. Coefficient values are listed in Table 4.6. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

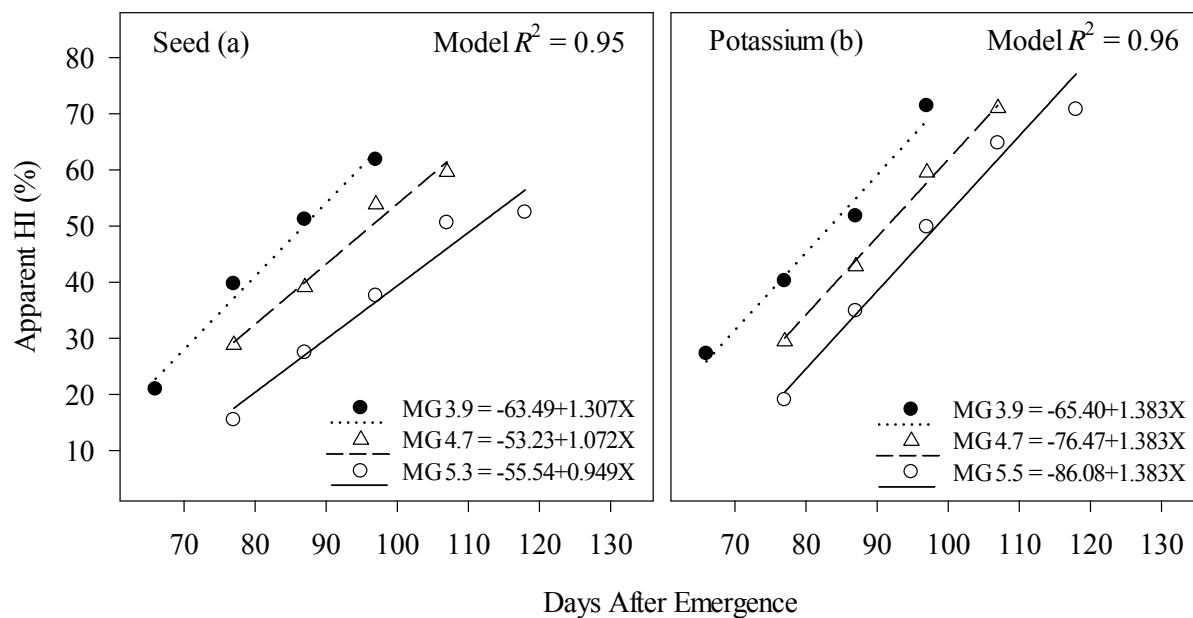


Fig. 4.7. Seasonal change of seed (a) and K (b) apparent harvest indices (ApHI) as predicted with a linear model of three different maturity group (MG) soybean cultivars for research trials conducted at the Pine Tree Research Station during 2013. The growth stages of each cultivar that correspond to the specific days after emergence are listed in Table 4.1.

CHAPTER 5

Critical Trifoliolate Leaf and Petiole Potassium Concentrations during the Reproductive Stages of Soybean

ABSTRACT

Critical nutrient concentration is used to determine whether the nutrient concentration within plant tissue is sufficient to produce maximum yield. We developed critical K concentrations in soybean [*Glycine max* (L.) Merr.] trifoliolate leaves and petioles across reproductive stages. Fifteen fully-expanded uppermost trifoliolate leaves with petioles plot⁻¹ were collected 7-12 times from the V5 to R7 stages across five site-years of research that evaluated multiple annual-K fertilization rates or cultivars from different maturity groups (MG). Both the trifoliolate leaf- and petiole-K concentrations regardless of site-year, cultivar, and K fertilization peaked around the R2 stage and declined linearly with time at average rates of -0.1974 g K kg⁻¹ d⁻¹ for leaves and -0.5585 g K kg⁻¹ d⁻¹ for petioles. The trifoliolate leaf- and petiole-K concentrations at the R2 to R6 stages explained 48 to 83% and 41 to 92%, respectively, of the variation in relative yield. The petiole-K concentration was a better predictor of relative yield than trifoliolate leaf-K concentration at the R2 stage where the predicted critical concentrations were 13.8 to 19.1 g K kg⁻¹ for leaf and 39.3 to 46.7 g K kg⁻¹ for petiole. The wider range of critical petiole-K concentrations at the R2 stage followed by a greater linear decline rate across reproductive stages suggests that growth stage as well as deficiency and sufficiency thresholds for petiole-K concentrations could be more easily categorized than for leaves. Overall, the ability to interpret the K nutritional status in leaves, petioles, or both tissues at numerous reproductive growth stages offers new tools to improve K management.

INTRODUCTION

Plant tissue analysis can be used to diagnose nutrient deficiencies before or after symptoms become visible provided a growth stage specific critical concentration has been properly developed. The critical nutrient concentration is a nutrient concentration range within a specific plant part above which near maximum yield is produced and below which yield loss is expected (Dow and Roberts, 1982; Mills and Jones, 1996). Critical concentrations are published for many crops and nutrients but some critical concentrations have been developed by identifying the normal distribution of a population of plant samples (e.g., survey) rather than correlating crop yield with tissue nutrient concentration from numerous site-years of fertilizer-response research. Although the survey-based nutrient concentration thresholds are of value, only research-based critical nutrient concentrations can be used to determine how the plant's nutrient status will influence yield.

Plant nutrient concentrations are known to vary among plant parts and plant development stages (Hanway and Weber, 1971; Sojka et al., 1985; Sadler et al., 1991). One of the most common problems encountered in diagnosing plant nutrient maladies from a plant sample is that the growth stage at the time of tissue collection may not match that for which the diagnostic information was developed. For example, critical nutrient concentrations for soybean are published for the uppermost recently mature trifoliolate leaves at the R1-2 stage (Mills and Jones, 1996; Sabbe et al., 2000). Some of the proposed critical nutrient concentrations are from surveys (Mills and Jones, 1996; Sabbe et al., 2000) and others are research-based (Grove et al., 1987; Slaton et al., 2010; Clover and Mallarino, 2013). The R1-2 growth stage represents the beginning of plant reproductive growth when the proportion of season-total dry matter accumulation by soybean is generally less than 30% (Egli and Leggett, 1973; Bender et al.,

2015). Despite widespread cultivation of soybean, critical nutrient concentrations have not been developed for growth stages other than the R1-2 stage.

Potassium deficiency is among the most common nutrient maladies experienced by soybean and yield increases from K fertilization are relatively common (Nelson et al., 1946; Jones et al., 1977; Camper et al., 1978; Borges and Mallarino, 2000). The critical K concentration in the recently mature uppermost trifoliolate leaves has been the research focus by several scientists and is reported to be a good indicator of the relative yield potential of soybean. Grove et al. (1987), Slaton et al. (2010), and Clover and Mallarino (2013) reported trifoliolate leaf-K concentration at the R1-2 stage is positively associated ($R^2 = 0.32-0.82$) with relative yield. However, Sartain et al. (1979) concluded that soybean seed yield was better correlated with the trifoliolate leaf-K concentration at early pod stage than at early bloom. Miller et al. (1961) reported a strong relationship between soybean yield and trifoliolate leaf-K concentration at the R4 stage ($R^2 = 0.53-0.72$).

The K concentration of ≥ 19 g K kg⁻¹ (Hanway and Johnson, 1985; Grove et al., 1987; Bell et al., 1995; Mills and Jones, 1996; Sabbe et al., 2000; Slaton et al., 2010; Clover and Mallarino, 2013) in the recently mature uppermost trifoliolate leaves of soybean at the R1-2 stage is considered sufficient and ≤ 15 g K kg⁻¹ (Hanway and Johnson, 1985; Bell et al., 1995; Mills and Jones, 1996; Sabbe et al., 2000; Slaton et al., 2010) is considered deficient. The concentration range from 15 to 19 g K kg⁻¹ is considered critical or low. We are aware of no research that has quantified the critical K concentration in the trifoliolate leaves of soybean beyond the R2 growth stage. Research has demonstrated that the total leaf-K concentration of soybean peaks between the late vegetative and early reproductive stages and then declines gradually with time (Hanway and Weber, 1971; Sumner, 1977; Sojka et al., 1985). Drossopoulos

et al. (1994) revealed that the K concentrations in the upper younger leaves of soybean peaked at the vegetative stage and plateaued up to the flowering (R1-2) stage and then declined linearly until leaf senescence (R7).

Plant petioles can also be used to monitor the K nutritional status during the growing season (Miller et al., 1961; Bell et al., 1987; Cassman et al., 1989). Although we could not find conclusive information for soybean, the petiole-K concentration of the uppermost fully-expanded leaf is highly associated with the yields of cotton (*Gossypium hirsutum* L., $R^2 = 0.53-0.61$; Cassman et al., 1989) and potato (*Solanum tuberosum* L.; $R^2 = 0.49-0.50$; Westermann et al., 1994). Petioles are used to monitor N, P, and K nutritional status for several vegetable and fruit crops (Ludwick, 1990). Limited research has shown that the petiole-K concentration of soybean peaks near the same time as leaf-K concentration, but the petiole-K concentrations are almost double that of the trifoliolate leaf-K and decline linearly with a wide range of concentration change across time (Hanway and Weber, 1971; Sojka et al., 1985).

The interpretation of the trifoliolate leaf-K concentration and perhaps other nutrients at any stage beyond the R1-2 may be possible if the decline rate of K concentration in plant tissues is relatively constant among years, cultivars, K fertility levels, and production systems. We could find no research that has described the dynamics of the uppermost mature trifoliolate leaf-K or petiole-K concentrations across soybean developmental stages. Characterizing the change of soybean trifoliolate leaf- and petiole-K concentrations across time and soybean growth stages would be of value for diagnosing the K nutritional status of soybean at more than a single growth stage. Our goal was to propose critical K concentrations for soybean in the trifoliolate leaves and petioles across reproductive developmental stages with specific objectives of i) characterizing the season-long dynamics of trifoliolate leaf- and petiole-K concentrations across a wide range of soil K

availabilities and cultivars of different MG and growth habits (e.g., determinate or indeterminate) and ii) correlating the relative soybean yield with the trifoliolate leaf- and petiole-K concentrations at each reproductive stage. Based on the cited literature we hypothesized that regardless of MG, growth habit, or K fertility level, both the trifoliolate leaf- and petiole-K concentrations would peak at blooming, increase as K fertility level increased, and then decline linearly across reproductive stages and be good indicators of the K nutritional status of irrigated soybean.

MATERIALS AND METHODS

Experimental Sites and Treatments

Three experiments were conducted to evaluate the seasonal change of trifoliolate leaf-K concentration across a range of soybean MG at the Pine Tree Research Station (PTRS), Colt, AR, USA in 2012 (PTRS-12), 2013 (PTRS-13) and 2014 (PTRS-14a). Each experimental site had been cropped to soybean in the previous year. Each of the PTRS-12, PTRS-13, and PTRS-14 research areas consisted of four adjacent tilled blocks that accommodated three, 7.6-m wide by 10-m long plots of each of three cultivars with each plot containing 20, 38-cm wide rows. Three glyphosate-resistant soybean cultivars including a MG 3.9 (Armor 39-R16 for PTRS-12 and PTRS-13 and Asgrow 3934 for PTRS-14a), MG 4.7 (Armor 48-R40), and MG 5.3 (Armor 52-R15 for PTRS-12) or 5.5 (Armor 55-R22 for PTRS-13 and PTRS-14a) were selected and randomized within each block. The MG 3.9 and 4.7 cultivars exhibited indeterminate growth habit and the MG 5.3 and 5.5 cultivars had a determinate growth habit.

Two additional experiments were conducted in 2014 to evaluate the seasonal change of trifoliolate leaf- and petiole-K concentrations across different K fertility levels and/or soybean MG at the Rice Research and Extension Center (RREC-14), Stuttgart, AR, USA and at the PTRS (PTRS-14b). Both of the experimental sites were cropped to rice (*Oryza sativa* L.) in 2013. The

PTRS-14b and RREC-14 sites were long-term K fertilization trials that were established in 2000 and 2007, respectively, that offered a range of soil- and annual fertilizer-K rates for this experiment. Both sites consisted of five annual-K rates ranging from 0 to 150 kg K ha⁻¹ yr⁻¹ in 37.5 kg K ha⁻¹ increments that were randomized within each block. The RREC-14 trial included a single indeterminate, MG 4.7 cultivar (Armor 47-R13) that was planted in each 4.6-m wide by 7.6-m long no-till plot of six blocks and each plot contained 20, 18-cm wide rows. The PTRS-14b trial included one indeterminate, MG 4.8 cultivar (Armor 48-R66) and one determinate, MG 5.5 cultivar (Armor 55-R22). Both cultivars were strip-planted across five no-till blocks where annual-K rate was the main-plot (4.0-m wide by 4.9-m long) and soybean cultivar was the subplot that contained 10, 38-cm wide rows of each cultivar. Selected soil and agronomic information and the planting dates for each experimental site are listed in Table 5.1.

Soil Sampling and Analysis

A composite soil sample was collected from each block before applying any fertilizer and consisted of six, 2-cm diam. soil cores from the 0- to 10-cm soil depth for the PTRS-12, PTRS-13, and PTRS-14a trials. A composite soil sample was collected from each main-plot (annual-K rate) of each block at RREC-14 and PTRS-14b. The composite soil samples were oven-dried at 55°C, crushed to pass a 2-mm sieve, and analyzed for soil organic matter by combustion (Schulte and Hopkins, 1996) and soil pH in a 1:2 v:v soil:water mixture (Sikora and Kissel, 2014). A subsample of 2.00±0.05 g soil was extracted with Mehlich-3 solution (Helmke and Sparks, 1996) for determining nutrient concentrations by inductively coupled plasma atomic emission spectroscopy (ICP-AES, Arcos-160 SOP, Spectro, NJ). The mean values of selected soil physicochemical properties of each experimental site are listed in Table 5.1.

Crop Management

The seeding rate of each cultivar at each experimental site was 73 kg ha⁻¹ which corresponds to a seed population of 417,600 seeds ha⁻¹. To ensure that plant nutrition was not limiting to plant growth and yield, the research area of each site was fertilized as outlined in Table 5.1. All research areas were flood-irrigated as needed, and irrigation and pest management followed University of Arkansas Cooperative Extension Service recommendations (University of Arkansas, 2000).

Plant Sampling and Analysis

For PTRS-12, PTRS-13, and PTRS-14a trials, a fully-expanded, trifoliolate leaf from one of the top three nodes of 15 plants plot⁻¹ was collected 7-12 times at 6-15 d intervals beginning at the V5 stage until the R7 stage (leaf senescence). For RREC-14 and PTRS-14b, a trifoliolate leaf along with petiole from the 3rd node from the top of 15 plants plot⁻¹ was collected 10 times every 6-10 d from the V5 to R6 stages. The average plant development stage as described by Fehr et al. (1971) was recorded at each sample time. The date, days after emergence (DAE), and growth stage that plant samples were collected in each trial are outlined in Table 5.2. In both sampling methods (one of the top three nodes vs. 3rd node from the top), the collected tissue samples were similar regarding nodal position. However, we collected tissue samples from the specific position (3rd node) of the plant at RREC-14 and PTRS-14b to avoid positional variation in the tissue-K concentrations (Hanway and Weber, 1971; Sojka et al., 1985; Sadler et al., 1991). The collected plant samples were dried at 60°C in a forced-draft oven for 7 d. The trifoliolate leaves were separated from the petioles after drying for samples collected at RREC-14 and PTRS-14b. Leaf and petiole samples were ground in a Wiley mill to <1 mm diam. particle size. A 0.250±.005 g

subsample was weighed, digested with concentrated HNO₃ and 30% H₂O₂ (Jones and Case, 1990), and the digests were analyzed by ICP-AES for K concentration.

At maturity, a 10 to 15 m² area within each block of each cultivar excluding the border rows was harvested with a small-plot combine for seed yield determination. The seed weight was adjusted to a uniform seed moisture content of 130 g H₂O kg⁻¹. The relative seed yield was calculated for each cultivar at PTRS-14b and RREC-14 by dividing the yield produced by soybean receiving each annual-K fertilization rate by the highest yield obtained among actual fertilizer-K rates and multiplying by 100.

Statistical Analysis

Soybean seed yield data from each site-year were analyzed using the MIXED procedure of SAS (v9.4, SAS Inst., Cary, NC). Data from PTRS-12, PTRS-13, and PTRS-14a were analyzed separately using a model that included the fixed effect of three soybean MG cultivars and the random effect of block. The ANOVA for RREC-14 included annual-K fertilization rate as a fixed effect and block as a random effect. The statistical model for PTRS-14b was a strip-plot treatment structure that included the fixed effects of annual-K fertilization rate as the main-plot factor and soybean cultivar as the subplot factor and the random effect of block. The means were separated by Fisher's protected LSD with differences interpreted as significant at the 0.05 probability level.

The replicate data of soybean trifoliolate leaf- and petiole- (if sampled) K concentrations of each cultivar and/or annual fertilizer-K rate of each site-year were regressed independently against DAE to predict the peak K concentration with the DAE that corresponded to the specific growth stage. The regression analyses were performed with a linear-slope model (model that has

two linear segments connected with each other; Schabenberger and Pierce, 2002) using the NLIN procedure of SAS.

To predict the decline rate of the trifoliolate leaf-K concentration across soybean cultivars after K concentration peaked, the replicate trifoliolate leaf-K concentration data from the R2 (where K concentration peaked) to R7 stages of PTRS-12, PTRS-13, and PTRS-14a were regressed together against DAE with a linear model using the MIXED procedure of SAS. The linear model included soybean cultivar ($n=3$) as the fixed effect and site-year ($n=3$) and block ($n=4$) as random effects.

To predict the diminishing trend of trifoliolate leaf- and petiole-K concentrations across annual-K fertilization rates after K concentration peaked, the replicate data from the growth stage where K concentrations peaked to the R6 stage for RREC-14 and PTRS-14b were regressed against DAE by trial using the MIXED procedure. The petiole- and trifoliolate leaf-K concentrations peaked at the R1 and R2 stages, respectively, for the MG 4.7 cultivar at RREC-14 and the MG 5.5 cultivar at PTRS-14b and at the R2 and R3 stages for the MG 4.8 cultivar at PTRS-14b. The linear regression models included the fixed effect of annual-K fertilization rates ($n=5$) for RREC-14 and the fixed effects of annual-K fertilization rates ($n=5$) and soybean cultivar ($n=2$) and their interaction for PTRS-14b. Both models also included five (PTRS-14b) or six (RREC-14) blocks as a random effect.

A linear model with the GLM and a linear-plateau (LP) model with the NLIN procedures of SAS were used to correlate relative soybean yield with the trifoliolate leaf- and petiole-K concentrations at the R1 to R6 stages. The studentized residuals distribution for all variables was tested to identify outliers (studentized residual $> \pm 2.5$) and the models were refit by omitting the outliers when appropriate.

The LP model had slightly higher R^2 values than the linear model for predicting soybean relative yield potential from trifoliolate leaf- and petiole-K concentrations and was used to calculate the critical range of trifoliolate leaf- and petiole-K concentrations at the R2 to R5 stages. The critical nutrient concentration range is defined multiple ways in the literature with definitions encompassing the concentrations at which 80 to 100% of the maximum growth or yield is produced (Ulrich and Hills, 1967; Ulrich and Hills, 1973; Dow and Roberts, 1982; Lanyon and Smith, 1985). Since the minimum significant yield reduction of soybean due to K deficiency is 5% (typically 5-20%) reported in the literature (Jones et al., 1977; Coale and Grove, 1990; Mallarino et al., 1991; Slaton et al., 2010; Clover and Mallarino, 2013), we used the 95% confidence limits (CL) of the join point of the LP model to define the critical range of leaf- and petiole-K concentrations. Trifoliolate leaf- and petiole-K concentrations above the upper CL were considered as sufficient, below the lower CL as deficient, and within the CL as low or critical.

RESULTS AND DISCUSSION

Soybean Seed Yield

Soybean seed yield was not significantly affected by soybean cultivar at PTRS-12 ($P = 0.079$, 3953 kg ha⁻¹) and PTRS-13 ($P = 0.473$, 2968 kg ha⁻¹). Soybean yields were different among cultivars at PTRS-14a ($P = 0.001$) with the MG 4.7 cultivar (4418 kg ha⁻¹) producing 13 and 74% greater yields (LSD 0.05 = 445 kg ha⁻¹) than the MG 5.5 (3898 kg ha⁻¹) and 3.9 (2533 kg ha⁻¹) cultivars, respectively. Soybean yield was significantly influenced by annual-K fertilization rate at RREC-14 and by the main effects of annual-K fertilization rate and soybean cultivar at PTRS-14b (Table 5.3). For RREC-14 and PTRS-14b, soybean receiving 38 to 150 kg K ha⁻¹ yr⁻¹ produced similar yields that were 9 to 15% and 12 to 19% greater, respectively, than the yield of soybean receiving no fertilizer-K. Averaged across annual-K fertilization rates at

PTRS-14b, the determinate MG 5.5 cultivar (4092 kg ha^{-1}) produced 24% greater seed yield than the indeterminate MG 4.8 cultivar (3302 kg ha^{-1}). The yield potential among soybean cultivars is known to vary (Boerma et al., 1982; Wilcox and Frankenberger, 1987; Ouattara and Weaver, 1994). The seed yield increases attributed to K fertilization in our studies were within the typical range (5 to 25%) of soybean yield responses to fertilizer-K reported in the literature (Coale and Grove, 1990; Mallarino et al., 1991; Slaton et al., 2010, 2013; Clover and Mallarino, 2013; and Parvej et al., 2015).

Seasonal Dynamics of Trifoliolate Leaf Potassium Concentration

The linear-slope model showed that regardless of soybean cultivar, annual-K fertilizer rate, or site-year, the K concentration in the uppermost recently mature trifoliolate leaves increased linearly or plateaued from the mid vegetative (V5-7) to the early reproductive stage (R1-3) and then declined linearly throughout reproductive growth (Table 5.4; Fig. 5.1a-l). The initial linear increase or plateau of the trifoliolate leaf-K concentration was not evident for the MG 3.9 cultivar at PTRS-13 (Fig. 5.1d) because the first leaf samples were collected at the onset of reproductive growth (Table 5.2). The trifoliolate leaf-K concentration decline as soybean progressed towards maturity in our five trials agrees with previous research and is attributed to increased dry matter production (i.e., dilution) and translocation of K to the developing seeds (Hanway and Weber, 1971; Sale and Campbell, 1980; Drossopoulos et al., 1994).

Three soybean cultivars belonging to different MG and planted at different times each year were used in trials at PTRS-12, PTRS-13, and PTRS-14a. The trifoliolate leaf-K concentration of each cultivar within each trial peaked at different DAE that coincided, on average, with the R2 stage (Table 5.4; Fig. 5.1a-i). The trifoliolate leaf-K concentration of soybean fertilized with five annual fertilizer-K rates peaked at the R2 stage for the MG 4.7

cultivar at RREC-14 (Fig. 5.1j) and MG 5.5 cultivar at PTRS-14b (Fig. 5.1l) and at the R3 stage for the MG 4.7 cultivar at PTRS-14b (Fig. 5.1k; Table 5.4). Among site-years, soybean cultivars, and annual fertilizer-K rates, the peak trifoliolate leaf-K concentrations ranged from 12.3 to 21.8 g K kg⁻¹, which represents K concentrations that would be considered deficient to optimal at the R1-2 stage (Hanway and Johnson, 1985; Slaton et al., 2010; Clover and Mallarino, 2013).

Trifoliolate leaf-K concentration at five site-years of research declined from the R2-3 growth stage to the R6-7 stage, so we examined the results to determine if the rate of decline was relatively uniform among site-years, cultivars, and K availability levels. The linear model showed that regardless of soybean cultivar or annual-K fertilization rate, the trifoliolate leaf-K concentration declined linearly with plant development. Within each trial a common negative slope was derived from the sources of variation (e.g., cultivars, site-years, or fertilizer-K rates) with average slope values of -0.1957 g K kg⁻¹ d⁻¹ for PTRS-12, PTRS-13, and PTRS-14a (Fig. 5.2a); -0.2028 g K kg⁻¹ d⁻¹ for RREC-14 (Fig. 5.2b); and -0.1937 g K kg⁻¹ d⁻¹ (Fig. 5.2c, d) for PTRS-14b (Table 5.5). The intercept was different among treatments within each trial indicating that the rate of decline was independent of cultivar or K availability. Averaged across PTRS-12, PTRS-13, and PTRS-14a, the trifoliolate leaf-K concentration among cultivars followed the order of cultivar MG 4.7 > MG 5.3/5.5 > MG 3.9 (Table 5.5; Fig. 5.2a). The trifoliolate leaf-K concentration increased either numerically or statistically with each increase in annual fertilizer-K rate for RREC-14 (Fig. 5.2b) and PTRS-14b (Fig. 5.2c, d).

When the trifoliolate leaf-K concentrations from all five trials between the R2 and R7 growth stages were regressed, the average slope was -0.1974 g K kg⁻¹ d⁻¹ (Table 5.5). The similarity of linear slope values among the five trials encompassing cultivars having a MG range of 3.9 to 5.5, different seeding dates, and multiple K availability levels suggests that predicting

critical trifoliolate leaf-K concentrations beyond the R2 stage is possible. When we regressed leaf-K concentrations of the top three nodes from Sadler et al. (1991) or K concentrations in the upper younger leaves from Drossopoulos et al. (1994) against DAE, leaf-K concentrations decreased linearly from the R2 to R6 stages at rates of -0.2523 and -0.2570 g K kg⁻¹ d⁻¹, respectively. The reason for relatively greater decline rates in their studies compared to our study is unknown. Soybean trifoliolate leaf-K concentrations are reported to be affected by soybean genotype (Keogh et al., 1977) and K availability (Clover and Mallarino, 2013). Research suggests that K fertilization increases trifoliolate leaf-K concentration when soybean yields respond positively to K fertilization, however, luxury consumption of K can increase leaf-K concentrations without a corresponding yield increase (Randall et al., 1997; Yin and Vyn, 2003; Clover and Mallarino, 2013).

Relative Soybean Yield and Trifoliolate Leaf Potassium Concentration

The linear and LP models showed significant relationships between relative soybean yield and trifoliolate leaf-K concentration at the R2 (Fig. 5.3a; LP only), R3 (Fig. 5.3b), R4 (Fig. 5.3c), R5 (Fig. 5.3d), R5.5 (Fig. 5.3e; linear), and R6 (Fig. 5.3f; linear) stages using data from RREC-14 and PTRS-14b (Table 5.6). The relationships at the R1 stage for both the linear ($P = 0.862$) and LP ($P = 0.446$) models and at the R2 stage for the linear model ($P = 0.063$) were not significant at the 0.05 probability level (not shown). The plateau segment of the LP model was not evident in the correlations for the R5.5 and R6 stages (not shown). The trifoliolate leaf-K concentrations across reproductive developmental stages explained 48 to 83% of the variation in relative soybean yield. The trifoliolate leaf-K concentration from the R3 to R5.5 stages accounted for 8 to 21% more relative yield variation than the K concentration at the R2 stage. Sartain et al. (1979) indicated that the trifoliolate leaf-K concentration at the early pod stage was

better correlated with soybean yield than the K concentration at the early bloom. The relationships reported by Miller et al. (1961) and Sartain et al. (1979) suggest that tissue-K concentration at the R3 to R4 stages may be better correlated with relative soybean yield than tissue-K concentration at the R1-2 stage (Grove et al., 1987; Slaton et al., 2010; Clover and Mallarino, 2013). The potential reasons for the stronger relationships for the R3 to R5.5 stages compared to the R2 stage (Table 5.6) may be because pod and seed numbers are better predictors of yield than flower number and flowers tend to abort more frequently than pods (Wiebold et al., 1981). The relationship between relative yield and trifoliolate leaf-K concentration at the R6 stage compared to the R3.0-5.5 stages was weaker and may be due to fewer data points. However, monitoring the K nutritional status of soybean plants as a guide for timely fertilization requires that the relationship be predicted using the earliest possible growth stage to avoid potential yield losses. Research-based information describing soybean yield response to K fertilization timing is scant and warrants further research. Nelson et al. (2005) showed that foliar-applied K at the V4, R1-2, and R3-4 stages increased soybean yield up to 834 kg ha⁻¹ compared to soybean that received no fertilizer-K. However, the yield increase was higher from K applied at the V4 or R1-2 stages than the R3-4 stage.

Critical Trifoliolate Leaf Potassium Concentration

The critical K concentrations in the trifoliolate leaves at the R2 stage that corresponded to the 95% CL of the join point of the LP model were 13.8 to 19.1 g K kg⁻¹ (Table 5.6; Fig. 5.3a). Trifoliolate leaf-K concentrations <13.8 g K kg⁻¹ were considered deficient and >19.1 g K kg⁻¹ were considered sufficient. Trifoliolate leaf-K concentrations ≤15.0 g K kg⁻¹ at the R2 stage have been reported as deficient numerous times in the literature and research clearly shows significant yield loss occurs below this threshold (Hanway and Johnson, 1985; Bell et al., 1995; Mills and

Jones, 1996; Sabbe et al., 2000; Slaton et al., 2010). The sufficient K concentration in the trifoliolate leaves at the R2 stage was within the 18.9 to 25.0 g K kg⁻¹ range reported in the literature (Hanway and Johnson, 1985; Grove et al., 1987; Bell et al., 1995; Mills and Jones, 1996; Sabbe et al., 2000; Slaton et al., 2010; Clover and Mallarino, 2013).

Based on the information in the literature and our five field trials, we developed a linear model that considered R2 stage trifoliolate leaf-K concentrations of 13.8 g K kg⁻¹ and 19.1 g K kg⁻¹ as the lower and upper boundaries, respectively, for probable deficiency with a linear slope of -0.1974 g K kg⁻¹ d⁻¹ defining the boundaries between the R2 and R6 stages (Fig. 5.4a). In the linear model, the R3, R4, R5, R5.5, and R6 growth stages corresponded to 10, 20, 30, 40, and 50 d after full-bloom (R2) and were estimated from our field observations (Table 5.2) and results reported by Zhang et al. (2004). The model indicated that across time (or reproductive developmental stages) trifoliolate leaf-K concentrations equal or less than the lower boundary would be deficient, concentrations equal or greater than the upper boundary would be sufficient, and concentrations between these two boundaries would be considered low (i.e., critical range, Fig. 5.4a). The calculated lower and upper boundaries of trifoliolate leaf-K concentrations were 11.8-17.1 g K kg⁻¹ at the R3, 9.9-15.2 g K kg⁻¹ at the R4, 7.9-13.2 g K kg⁻¹ at the R5, 5.9-11.2 g K kg⁻¹ at the R5.5, and 3.9-9.2 g K kg⁻¹ at the R6 stages from the proposed model. These critical ranges will vary with the duration of each reproductive growth stage and require knowledge of the actual growth stage or the date of the R2 stage (i.e., to calculate the days after R2 stage). Research that includes a wide range of soybean genotypes, soil textures, K availability levels, and agroclimatic conditions is needed to validate whether these preliminary critical trifoliolate leaf-K concentrations model can accurately predict K deficiency beyond the R2 stage.

Seasonal Dynamics of Petiole Potassium Concentration

The K concentration of petioles from the third node from the top of the plant also increased linearly during late vegetative growth, peaked during early reproductive growth (R1-2), and declined linearly as soybean progressed into reproductive development (Table 5.4; Fig. 5.5b, c). The absence of an initial linear increase of the petiole-K concentration from the vegetative to the early reproductive stage for RREC-14 (Fig. 5.5a) was because the first sample coincided with the onset of reproductive growth (Table 5.2). The linear-slope model showed that the peak petiole-K concentration (22.8 to 53.7 g K kg⁻¹), across annual-K fertilizer rates and soybean cultivars, occurred 44-50 DAE, at the R1 stage for the MG 4.7 cultivar at RREC-14 and the MG 5.5 cultivar at PTRS-14b and at the R2 stage for the MG 4.8 cultivar at PTRS-14b (Table 5.4; Fig. 5.5). Available research indicate petiole-K concentrations peak near blooming and decline linearly with time (Hanway and Weber, 1971; Sojka et al., 1985). The peak petiole-K concentrations (22.8 to 53.7 g K kg⁻¹) in our study were about double that of the peak trifoliolate leaf-K concentrations (12.3 to 22.3 g K kg⁻¹; Table 5.4) which agrees with the findings of Hanway and Weber (1971) and Sojka et al. (1985).

We also evaluated the linear decline of the petiole-K concentration after K concentration peaked at the R1-2 stage across five annual-K fertilization rates with one (RREC-14) or two (PTRS-14b) soybean cultivars. The linear model showed that the petiole-K concentration decreased linearly with a common slope coefficient of -0.5535 g K kg⁻¹ d⁻¹, regardless of annual-fertilizer-K rate for RREC-14 (Table 5.7; Fig. 5.6a). For PTRS-14b, the slope values were different among annual fertilizer-K rates ranging from -0.3998 to -0.6080 g K kg⁻¹ d⁻¹ due to the significant interaction between annual fertilizer-K rate and DAE (Fig. 5.6b, c). However, the slope values of -0.5202 to -0.6080 g K kg⁻¹ d⁻¹ for soybean fertilized with 38 to 150 kg K ha⁻¹ yr⁻¹

were statistically similar and higher than the slope value of $-0.3998 \text{ g K kg}^{-1} \text{ d}^{-1}$ for soybean receiving $0 \text{ kg K ha}^{-1} \text{ yr}^{-1}$. The average decline rate of petiole-K concentration for the K-fertilized soybean grown at PTRS-14b was $-0.5634 \text{ g K kg}^{-1} \text{ d}^{-1}$ (Table 5.7). The lower decline rate for soybean receiving no fertilizer-K at PTRS-14b was probably due to the already very low petiole-K concentrations (e.g., intercepts) present in both cultivars at the R2 stage caused by low soil-K availability. The slope values for soybean grown at RREC-14 and for the soybean grown at PTRS-14b were not statistically compared, but were numerically similar, averaging $-0.5585 \text{ g K kg}^{-1} \text{ d}^{-1}$.

The linear model also indicated that the petiole-K concentration for a particular time or reproductive stage increased with each increase in annual-K fertilization rate for RREC-14 (intercept; Table 5.7; Fig. 5.6a). Regardless of soybean cultivar at PTRS-14b, the petiole-K concentration during the reproductive stages (R2-6) increased statistically or numerically as annual fertilizer-K rate increased (Fig. 5.6b, c). We could find no information in the literature describing the seasonal dynamics of petiole-K concentration as affected by K availability. Miller et al. (1961) showed that petiole-K concentrations on both the lower- and upper-half of soybean plants at the R4 stage increased as fertilizer-K rate increased.

Relative Soybean Yield and Petiole Potassium Concentration

In order to predict a critical petiole-K concentration for a particular growth stage, we evaluated the relationships between relative soybean yield and petiole-K concentrations at the R1 to R6 stages. The linear and LP models showed significant relationships between relative yield and petiole-K concentrations at the R2 (Fig. 5.7a), R3 (Fig. 5.7b), R4 (Fig. 5.7c), R5 (Fig. 5.7d), R5.5 (Fig. 5.7e; linear), and R6 (Fig. 5.7f; linear) stages (Table 5.6). The relationship at the R1 stage was not significant at the 0.05 probability level for either the linear ($P = 0.735$) or LP ($P = 0.999$) models (not shown). The LP models for the R5.5 and R6 stages were not valid due to the

lack of a plateau (not shown). The petiole-K concentrations from the R2 to R6 stages accounted for 41 to 92% of the variability in relative soybean yield. Both the linear and LP models showed that the petiole-K concentration at the R2 stage had the highest numerical R^2 value and it declined as plant development advanced to the R3 to R6 stages (Table 5.6). We could find no research that evaluated the relationship between relative soybean yield and petiole-K concentration of the uppermost recently mature leaves at any growth stage. However, when we regressed soybean yield from Miller et al. (1961) against the petiole-K concentrations of the upper-half of the plant at the R4 stage, we found a LP relationship that explained 75% of the variation in soybean yield [$y = 78.1 + 142.9x$; $x = 13.5 \text{ g K kg}^{-1}$; $P < 0.001$; not shown]. Cassman et al. (1989) showed that the petiole-K concentration of the uppermost fully-expanded leaf of cotton at the full-bloom stage accounted for 53 to 61% variation in relative cotton yield.

Critical Petiole Potassium Concentration

The critical petiole-K concentrations at the R2 stage that corresponded to 95% CL of the LP model join point were 39.3 and 46.7 g K kg⁻¹ (Table 5.6; Fig. 5.7a), which were more than double the concentrations that defined the critical trifoliolate leaf-K concentration at the R2 stage (13.8-19.1 g K kg⁻¹). Hanway and Weber (1971) and Sojka et al. (1985) also reported that petiole-K concentrations around blooming were nearly twice the concentration of trifoliolate leaves. The petiole-K concentrations of ≤ 39.2 and ≥ 46.8 g K kg⁻¹ were, therefore, considered deficient and sufficient, respectively, petiole-K concentration thresholds at the R2 stage. We could find no information in the literature regarding critical petiole-K concentrations for soybean at any growth stage.

The deficient petiole-K concentration defining the lower boundary of the 95% CL were 35.2 g K kg⁻¹ at the R3, 28.3 g K kg⁻¹ at the R4, and 22.5 g K kg⁻¹ at the R5 stages. These

deficient petiole-K concentrations including 39.3 g K kg⁻¹ at the R2 stage also declined linearly from the R2 to R5 stages (0 to 30 days after R2) with a slope value of -0.5730 g K kg⁻¹ d⁻¹ ($Y = 39.9 - 0.5730x$; $P < 0.001$; $R^2 = 0.99$; not shown), which was very close to our average slope value of -0.5585 g K kg⁻¹ d⁻¹ (Table 5.7). Based on the critical petiole-K concentration thresholds at the R2 stage (39.3 to 46.7 g K kg⁻¹) and the average rate of petiole-K decline (-0.5585 g K kg⁻¹ d⁻¹) from the R2 stage, we defined the critical petiole-K concentrations across reproductive developmental stages (Fig. 5.4b). This preliminary model shows that the deficient petiole-K concentrations at R3, R4, R5, R5.5, and R6 stages were 33.7, 28.1, 22.5, 17.0, and 11.4 g K kg⁻¹, respectively. Additional research across a range of years, soils, K fertility levels, and soybean cultivars is needed to validate the accuracy of our proposed critical petiole-K concentrations across the reproductive developmental stages.

Comparison between Critical Trifoliolate Leaf and Petiole Potassium Concentrations

We did not compare K concentrations between trifoliolate leaves and petioles, but our study showed that the petiole-K concentrations across annual fertilizer-K rates had a wider range of change from the R2 to R6 stages (30.3-49.3 g K kg⁻¹ at the R2 stage to 3.3-19.3 g K kg⁻¹ at the R6 stage; Fig. 5.6) than the trifoliolate leaf-K concentrations (15.2-21.3 g K kg⁻¹ to 5.7-12.1 g K kg⁻¹; Fig. 5.2). The intercept and linear slope values were approximately two and three times, respectively, greater for the petiole-K (Table 5.7) than the trifoliolate leaf-K (Table 5.5) concentrations. The wider range of critical petiole-K concentrations from one growth stage to the other suggests that growth stage as well as deficiency and sufficiency thresholds for petiole-K concentrations could be more easily categorized. For example, according to our models the critical petiole-K concentrations were 33.7 to 41.1 g K kg⁻¹ at the R3, 28.1 to 35.5 g K kg⁻¹ at the R4, 22.5 to 29.9 g K kg⁻¹ at the R5, 17.0 to 24.4 g K kg⁻¹ at the R5.5, and 11.4 to 18.8 g K kg⁻¹ at

the R6 stages, which are higher than the values and ranges of the critical trifoliolate leaf-K concentrations of 11.8 to 17.1 g K kg⁻¹ at the R3, 9.9 to 15.2 g K kg⁻¹ at the R4, 7.9 to 13.2 g K kg⁻¹ at the R5, 5.9 to 11.2 g K kg⁻¹ at the R5.5, and 3.9 to 9.2 g K kg⁻¹ at the R6 stages. Our results suggest that soybean petioles may be an equally good or perhaps better tissue than trifoliolate leaves for monitoring the K nutritional status of soybean during reproductive growth. Mills and Jones (1996) summarized that petioles are a better tissue than the uppermost fully-expanded leaves for monitoring the nutritional status in cotton, potato, sugar beet (*Beta vulgaris*), and some vegetables. The higher nutrient concentrations in the petioles than in the leaves is because petioles i) are not an active site for nutrient metabolism, ii) serve as a conductive tissue which acts as a 'pipeline' for nutrient transport, and iii) store nutrients when plants are under stress.

CONCLUSIONS

The trifoliolate leaf- and petiole-K concentrations both peaked around blooming (R2 stage) and then declined linearly at a constant rate of -0.1974 g K kg⁻¹ d⁻¹ for the leaves and -0.5585 g K kg⁻¹ d⁻¹ for the petioles, regardless of soybean cultivar, growth habit, or annual fertilizer-K rate. The uniform rate of decline in K concentrations for each of these tissues extends our ability to interpret tissue-K concentrations at growth stages beyond R2. The petiole- and leaf-K concentrations from the R2 to R5.5 stages were highly correlated with relative soybean yield. Petiole-K concentrations at the R2 stage explained more of the relative yield variability than trifoliolate leaf-K concentrations, but the strength of the relationships from the R3 to R5.5 stages was comparable. The twofold higher value and range of the critical K concentrations at the R2 stage followed by a nearly threefold greater linear decline rate across the reproductive stages for the petioles (39.3 to 46.7 g K kg⁻¹ with -0.5585 g K kg⁻¹ d⁻¹) compared to the trifoliolate leaves (13.8 to 19.1 g K kg⁻¹ with -0.1974 g K kg⁻¹ d⁻¹) may allow for more accurate separation of the

deficient- and sufficient-K concentrations within a growth stage as well as between the growth stages. Overall, the ability to interpret the K nutritional status in leaves, petioles, or both tissues at numerous reproductive growth stages will improve K management. Agricultural practitioner's will be able to monitor and possibly correct K nutritional problems during the growing season across a range of growth stages which could help increase soybean yield and quality, especially for high yielding environments.

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Table 5.1. Selected soil and agronomic information, soil physicochemical property means, and nutrient management for research trials conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12), 2013 (PTRS-13), and 2014 (PTRS-14a) and for long-term K fertilization trials conducted with five annual fertilizer-K rates at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station (PTRS-14b) in 2014.

Site-year	Annual-K rate kg K ha ⁻¹ yr ⁻¹	Soil classification		Date planted day/month	Organic matter g kg ⁻¹	Soil pH	Mehlich-3 extractable soil nutrients					Nutrient supplied‡§		
		Series	Group†				P	K	Ca	Mg	S	P	K	B
							-----mg kg ⁻¹ -----					-----kg ha ⁻¹ -----		
PTRS-12	-	Calhoun	TG	22 May	22	7.1	15	64	1643	302	8	25	73¶	0.6
PTRS-13	-	Calloway	AF	26 June	23	7.3	58	96	1762	287	11	0	70	0.6
PTRS-14a	-	Calhoun	TG	22 May	26	7.1	13	68	1628	263	7	35	100	0.6
RREC-14	0	Dewitt	TA	24 Apr.	23	5.5	32	99	883	101	6	26	0	0.0
	38	Dewitt	TA	24 Apr.	-	5.6	31	124	912	105	7	26	38	0.0
	75	Dewitt	TA	24 Apr.	-	5.5	30	139	816	96	7	26	75	0.0
	113	Dewitt	TA	24 Apr.	-	5.5	32	152	834	95	6	26	113	0.0
	150	Dewitt	TA	24 Apr.	-	5.5	33	177	805	94	7	26	150	0.0
PTRS-14b	0	Calhoun	TG	22 May	30	7.9	30	76	2755	409	24	26	0	1.1
	38	Calhoun	TG	22 May	-	7.9	26	88	2788	395	26	26	38	1.1
	75	Calhoun	TG	22 May	-	7.8	28	93	2685	385	28	26	75	1.1
	113	Calhoun	TG	22 May	-	7.8	30	107	2671	394	27	26	113	1.1
	150	Calhoun	TG	22 May	-	7.8	29	128	2635	387	26	26	150	1.1

† AF, Aquic Fraglossudalfs; TA, Typic Albaqualfs; TG, Typic Glossaqualfs.

‡ Phosphorus, K, and B were applied as triple superphosphate (200 g P kg⁻¹), muriate of potash (500 g K kg⁻¹), and Na₂B₈O₁₃·4H₂O (205 g B kg⁻¹), respectively. All fertilizers at each site were broadcast to the soil surface before planting except for B at PTRS-12, PTRS-13, and PTRS-14, which was sprayed after soybean emergence.

§ For PTRS-12, 22 kg S and 11 kg Mg ha⁻¹ were applied as K₂SO₄·2MgSO₄ (180 g K, 215 g S, and 105 g Mg kg⁻¹) and at RREC-14, 435 kg ha⁻¹ pelleted lime was applied two weeks before planting.

¶ A total of 73 kg K ha⁻¹ was applied as 55 kg K ha⁻¹ was applied as muriate of potash (500 g K kg⁻¹) and 18 kg K ha⁻¹ as K₂SO₄·2MgSO₄ (180 g K, 215 g S, and 105 g Mg kg⁻¹).

Table 5.2. The date, days after emergence (DAE), and growth stage that plant samples were collected for three cultivars belonging to different maturity groups (MG) for research conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12), 2013 (PTRS-13), and 2014 (PTRS-14a) and for one or two cultivars in long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station (PTRS-14b) in 2014.

Sample time	Sample date	DAE	Growth stage ^{†‡}		
			MG 3.9	MG 4.7/4.8§	MG 5.3/5.5¶
<u>PTRS-12</u>					
1	26 June	28	R1	R0	V5
2	11 July	43	R2	R2	R0
3	24 July	56	R3	R2	R2
4	7 Aug.	70	R5	R4	R3
5	22 Aug.	85	R5.5	R5	R5
6	5 Sep.	99	R6	R5.5	R5.5
7	12 Sep.	106	R7	-	-
	19 Sep.	113	-	R6.5	-
	3 Oct.	127	-	-	R7
<u>PTRS-13</u>					
1	25 July	22	R1	V6	V6
2	6 Aug.	34	R3	R2	V9
3	15 Aug.	43	R4	R3	R2
4	27 Aug.	55	R5	R5	R4
5	7 Sep.	66	R5.5	R5.5	R5
6	18 Sep.	77	R6	R5.5	R5.5
7	28 Sep.	87	R7	R6.5	R5.5
8	8 Oct.	97	-	-	R6.5
<u>PTRS-14a</u>					
1	25 June	27	V6	V6	V6
2	3 July	35	R2	R1	V8
3	9 July	41	R3	R2	R0
4	16 July	48	R3.5	R3	R1
5	24 July	56	R4	R3	R2
6	30 July	62	R5	R4	R3
7	6 Aug.	69	R5.5	R5	R4
8	14 Aug.	77	R5.5	R5.5	R4
9	21 Aug.	84	R6	R5.5	R5
10	31 Aug.	94	R7	R6.5	R5.5
11	10 Sep.	104	-	R7	R6
12	20 Sep.	114	-	-	R6.5
<u>RREC-14</u>					
1	18 June	48	-	R1	-
2	26 June	56	-	R2	-
3	2 July	62	-	R3	-
4	10 July	70	-	R4	-
5	16 July	76	-	R4.5	-
6	23 July	83	-	R5	-

Table 5.2. (Cont.)

Sample time	Sample date	DAE	Growth stage†‡		
			MG 3.9	MG 4.7/4.8§	MG 5.3/5.5¶
7	30 July	91	-	R5.5	-
8	6 Aug.	97	-	R5.5	-
9	13 Aug.	104	-	R6	-
10	21 Aug.	112	-	R6	-
			<u>PTRS-14b</u>		
1	3 July	35	-	R1	V8
2	9 July	41	-	R2	V9
3	16 July	48	-	R2	R1
4	24 July	56	-	R3	R2
5	30 July	62	-	R3.5	R3
6	6 Aug.	69	-	R4.5	R3.5
7	14 Aug.	77	-	R5	R4
8	21 Aug.	84	-	R5.5	R5
9	31 Aug.	94	-	R5.5	R5.5
10	10 Sep.	104	-	R6	R5.5

† Growth stage key: Fehr et al. (1971).

‡ Additional growth stages not defined by Fehr et al. (1971): R0, Plants had flower clusters, but the flowers were not open; R3.5, R4.5, and R6.5, one-half of the plants were in the growth stages immediately above and below the listed value; and R5.5, areas of pod cavities at one of the top four nodes were 50% filled by developing seeds.

§ A MG 4.7 cultivar was used for PTRS-12, PTRS-13, PTRS-14a, and RREC-14 and a MG 4.8 cultivar was used for PTRS-14b.

¶ A MG 5.3 cultivar was used for PTRS-12 and a MG 5.5 cultivar was used for PTRS-13, PTRS-14a, and PTRS-14b.

Table 5.3. Soybean seed yield as affected by annual fertilizer-K rate for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station (PTRS-14b) in 2014.

Annual fertilizer-K rate or source of variation	Seed yield	
	RREC-14	PTRS-14b
	-----kg ha ⁻¹ -----	
0	4465	3271
38	4905	3665
75	4885	3771
113	5120	3877
150	5114	3901
LSD(0.05)	283	378
	<u><i>P</i> values</u>	
Annual fertilizer-K rate (K)	0.001	0.027
Cultivar (C)	-	0.002
K × C	-	0.565

Table 5.4. Intercept and slope coefficients predicting the number of days after emergence (DAE) that corresponded to a specific growth stage where trifoliolate leaf- and/or petiole-K concentrations (KC) peaked for research trials conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12), 2013 (PTRS-13), and 2014 (PTRS-14a) with three soybean cultivars belonging to different maturity groups (MG) and for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station (PTRS-14b) in 2014 with five annual fertilizer-K rates and one or two cultivars.

Site-year	MG	Annual fertilizer-K rate kg K ha ⁻¹ yr ⁻¹	Linear-slope model ^{†‡} coefficients				Peak or join point		
			Intercept g K kg ⁻¹	1 st slope -----g K kg ⁻¹ d ⁻¹ -----	2 nd slope	R ²	KC g K kg ⁻¹	DAE d	Growth stage
<u>Trifoliolate leaf</u>									
PTRS-12	3.9	-	8.9	0.159§	-0.173	0.80	16.1	45	R2
		4.7	8.9	0.168	-0.172	0.89	18.1	55	R2
		5.3	5.5	0.215	-0.170	0.83	16.3	50	R1.5
PTRS-13	3.9	-	19.4	0.063§	-0.139	0.89	20.5	18§	R1
		4.7	20.5	-0.008§	-0.076	0.48	20.2	33	R2
		5.5	16.4	0.105§	-0.236	0.96	20.4	38	R1.5
PTRS-14a	3.9	-	17.5	0.077§	-0.255	0.90	20.8	43	R3
		4.7	14.2	0.124	-0.295	0.94	20.6	52	R3
		5.5	15.6	0.131§	-0.267	0.89	21.8	47	R1
RREC-14	4.7	0	15.8§	0.034§	-0.202	0.86	17.6	53§	R1.5
		38	14.4§	0.092§	-0.228	0.89	19.6	56§	R2
		75	6.6§	0.258§	-0.206	0.83	21.0	56§	R2
		113	14.9§	0.114§	-0.199	0.85	21.3	56§	R2
		150	13.9§	0.150§	-0.193	0.79	22.3	56§	R2
PTRS-14b	4.8	0	1.3§	0.225	-0.188	0.57	14.4	58	R3
		38	1.7§	0.264	-0.225	0.85	17.0	58	R3
		75	3.4	0.277	-0.223	0.87	19.5	58	R3
		113	1.8§	0.329	-0.200	0.77	20.9	58	R3
		150	0.7§	0.350	-0.168	0.83	20.3	56	R3
	5.5	0	3.0§	0.179	-0.136	0.77	12.3	52	R1.5
		38	-1.0§	0.325	-0.192	0.81	15.9	52	R1.5
		75	-7.1	0.519	-0.212	0.91	19.4	51	R1.5
		113	1.8§	0.299	-0.213	0.80	19.4	59	R2
		150	2.1§	0.295	-0.194	0.80	19.5	59	R2

Table 5.4. (Cont.)

Site-year	MG	Annual fertilizer-K rate kg K ha ⁻¹ yr ⁻¹	Linear-slope model†‡ coefficients				Peak or join point		
			Intercept g K kg ⁻¹	1 st slope -----g K kg ⁻¹ d ⁻¹ ----- <u>Petiole</u>	2 nd slope	R ²	KC g K kg ⁻¹	DAE d	Growth stage
RREC-14	4.7	0	32.2	0.025§	-0.505	0.91	33.4	48§	R1
		38	38.6	0.053§	-0.597	0.93	41.1	48§	R1
		75	42.4	0.043§	-0.551	0.91	44.5	48§	R1
		113	46.1	0.043§	-0.572	0.91	48.2	48§	R1
		150	46.9	0.043§	-0.516	0.90	49.0	48§	R1
PTRS-14b	4.8	0	-21.2§	1.019	-0.511	0.67	28.7	49	R2
		38	-75.2	2.653	-0.674	0.92	41.5	44	R2
		75	-17.3	1.320	-0.734	0.91	47.4	49	R2
		113	-12.4§	1.284	-0.740	0.91	51.8	50	R2
		150	-7.7§	1.228	-0.697	0.90	53.7	50	R2
	5.5	0	-13.4§	0.755	-0.354	0.76	22.8	48	R1
		38	-53.9	1.964	-0.539	0.86	34.5	45	R1
		75	-68.5	2.453	-0.650	0.89	44.3	46	R1
		113	-24.7	1.375	-0.596	0.86	44.1	50	R1
		150	-29.2	1.521	-0.534	0.88	45.3	49	R1

† Data were analyzed for each site-year, cultivar (MG), and/or annual fertilizer-K rate. Each model was significant at the 0.0001 probability level.

‡ The linear-slope model [KC = {intercept + (1st slope × DAE)} + {intercept + (2nd slope × DAE)}] is a model that has two linear segments connected with each other (Schabenberger and Pierce, 2002).

§ Coefficients and join points are not significantly different from zero at the 0.05 probability level.

Table 5.5. Intercept and linear slope coefficients predicting the decline rate of trifoliolate leaf-K concentration (LKC) as a function of time (T) for three soybean cultivars belonging to three maturity groups (MG) for research trials conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12), 2013 (PTRS-13), and 2014 (PTRS-14a) and for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station (PTRS-14b) in 2014 that included five annual fertilizer-K rates and one or two cultivars.

Cultivar MG	Annual-K rate kg K ha ⁻¹ yr ⁻¹	Linear model [†] coefficients		R ²
		Intercept g K kg ⁻¹	Slope g K kg ⁻¹ d ⁻¹	
<u>Averaged across PTRS-12, PTRS-13, and PTRS-14a</u>				
MG 3.9	-	26.5 c‡	-0.1957 a	0.82
MG 4.7	-	28.9 a	-0.1957 a	
MG 5.3/5.5§	-	27.3 b	-0.1957 a	
SE		0.6	0.0065	
<u>RREC-14</u>				
MG 4.7	0	28.2 d	-0.2028 a	0.87
	38	30.2 c	-0.2028 a	
	75	32.3 b	-0.2028 a	
	113	32.6 b	-0.2028 a	
	150	33.9 a	-0.2028 a	
SE		0.5	0.0055	
<u>PTRS-14b</u>				
MG 4.8	0	25.4 e	-0.1937 a	0.86
	38	27.4 d	-0.1937 a	
	75	30.1 b	-0.1937 a	
	113	31.5 a	-0.1937 a	
	150	31.8 a	-0.1937 a	
MG 5.5	0	24.1 f	-0.1937 a	
	38	26.1 e	-0.1937 a	
	75	28.7 c	-0.1937 a	
	113	30.2 b	-0.1937 a	
	150	30.4 b	-0.1937 a	
SE		0.5	0.0053	
Average slope (all site-years)			-0.1974	
Average SE (all site-years)			0.0058	

[†] LKC = intercept + (slope × T).

[‡] Within each site-year, values in the same column followed by different letters are significantly different at the 0.05 probability level.

[§] A MG 5.3 cultivar was used for PTRS-12 and a MG 5.5 cultivar was used for PTRS-13, PTRS-14a, and PTRS-14b.

Table 5.6. Relationships between soybean relative yield (RY) and trifoliolate leaf- and petiole-K concentrations (KC) at the R2 to R6 growth stage as predicted with linear (L) and linear-plateau (LP) models for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station in 2014 (PTRS-14b).

Growth stage†	Model‡	Coefficients			Join point	
		Intercept g K kg ⁻¹	Slope g K kg ⁻¹ d ⁻¹	R ²	KC§ g K kg ⁻¹	RY %
<u>Trifoliolate leaf</u>						
R2¶	LP	53.2	2.649	0.62	16.5	96.8
	SE	13.3	0.950	-	1.2	3.3
R3	L	67.7	1.577	0.77	-	-
	SE	4.0	0.236	-	-	-
	LP	64.8	1.766	0.83	19.5	99.2
	SE	4.2	0.257	-	1.1	1.7
R4#	L	70.6	1.446	0.73	-	-
	SE	4.1	0.246	-	-	-
	LP	69.6	1.512	0.75	19.3	98.8
	SE	4.8	0.305	-	1.5	2.4
R5	L	71.3	1.714	0.80	-	-
	SE	3.3	0.238	-	-	-
	LP	67.0	2.128	0.80	14.6	98.1
	SE	5.3	0.463	-	1.0	2.4
R5.5††	L	76.2	1.667	0.70	-	-
	SE	3.4	0.302	-	-	-
R6¶	L	85.3	1.083	0.48	-	-
	SE	3.9	0.396	-	-	-
<u>Petiole</u>						
R2¶	L	71.8	0.605	0.85	-	-
	SE	2.8	0.072	-	-	-
	LP	67.4	0.740	0.92	43.0	99.2
	SE	2.6	0.074	-	1.7	1.4
R3	L	78.7	0.427	0.81	-	-
	SE	2.2	0.060	-	-	-
	LP	75.8	0.534	0.85	43.0	98.7
	SE	3.1	0.103	-	3.6	2.0
R4#	L	77.8	0.608	0.81	-	-
	SE	2.3	0.081	-	-	-
	LP	76.1	0.682	0.84	33.7	99.2
	SE	2.5	0.098	-	2.5	1.9
R5	L	81.7	0.559	0.75	-	-
	SE	2.2	0.090	-	-	-
	LP	79.6	0.687	0.79	28.9	99.4
	SE	2.5	0.121	-	3.0	2.2
R5.5††	L	85.2	0.603	0.65	-	-
	SE	2.0	0.122	-	-	-

Table 5.6. (Cont.)

Growth stage†	Model‡	Coefficients			Join point	
		Intercept g K kg ⁻¹	Slope g K kg ⁻¹ d ⁻¹	R ²	KC§ g K kg ⁻¹	RY %
R6¶	L	90.6	0.552	0.41	-	-
	SE	2.4	0.232	-	-	-

† The relationships between RY and K concentration in the trifoliolate leaf ($P = 0.862$ for L and 0.446 for LP) or petiole ($P = 0.735$ for L and 0.999 for LP) at the R1 stage were not significant at the 0.05 probability level. The L model for the trifoliolate leaf-K at the R2 growth stage was not significant at the 0.05 probability level ($P = 0.063$).

‡ Each model [RY = intercept + (slope × KC)] was significant at the 0.001 probability level except for the LP model at the R2 stage for trifoliolate leaf ($P = 0.005$) and L model at the R6 stage for both trifoliolate leaf ($P = 0.026$) and petiole ($P = 0.045$).

§ At the R2 stage, the 95% confidence limits (CL) of the join point of the LP model were 13.8-19.1 g K kg⁻¹ for leaf and 39.3-46.7 g K kg⁻¹ for petiole. These concentrations were considered as low or critical range (CR) for both tissues. Tissue concentrations above and below the CR were considered as sufficient and deficient, respectively.

¶ Tissue samples were collected twice during the R2 growth stage for the MG 4.8 cultivar at PTRS-14b and the R6 growth stage for the MG 4.7 cultivar at RREC-14 (Table 5.2). Tissue-K concentrations from the second sampling were used in regression analyses.

Tissue samples were not collected at the R4 growth stage for the MG 4.8 cultivar at PTRS-14b (Table 5.2). The mean of K concentrations for the R3.5 and R4.5 stages were used for regression analyses.

†† Tissue samples were collected twice during R5.5 growth stage for both RREC-14 and PTRS-14b (Table 5.2). The mean K concentrations of the two sample times was used the regression analyses.

Table 5.7. Intercept and linear slope coefficients predicting the decline rate of petiole-K concentration (PKC) as a function of time (T) as affected by five annual fertilizer-K rates and one or two soybean cultivars belonging to different maturity groups (MG) for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) and Pine Tree Research Station (PTRS-14b) in 2014.

Cultivar MG	Annual-K rate kg K ha ⁻¹ yr ⁻¹	Linear model† coefficients		
		Intercept g K kg ⁻¹	Slope g K kg ⁻¹ d ⁻¹	R ²
		<u>RREC-14</u>		
MG 4.7	0	62.0 e‡	-0.5535 a	0.92
	38	66.3 d	-0.5535 a	
	75	71.0 c	-0.5535 a	
	113	74.1 b	-0.5535 a	
	150	77.0 a	-0.5535 a	
SE		1.0	0.0105	
		<u>PTRS-14b</u>		
MG 4.8	0	45.0 c	-0.3998 b	0.88
	38	62.0 b	-0.5607 a	
	75	72.3 a	-0.6080 a	
	113	73.9 a	-0.5646 a	
	150	72.9 a	-0.5202 a	
MG 5.5	0	42.4 c	-0.3998 b	
	38	59.4 b	-0.5607 a	
	75	69.7 a	-0.6080 a	
	113	71.3 a	-0.5646 a	
	150	70.3 a	-0.5202 a	
SE		2.1	0.0272	
Average slope (PTRS-14b)			-0.5634§	
Average slope (all site-years)			-0.5585¶	
Average SE (all site-years)			0.0189	

† PKC = intercept + (slope × T).

‡ Different letters next to mean values in the same column within each site-year represent significant difference at the 0.05 probability level.

§ Average slope for the annual fertilizer-K rates of 38 to 150 kg K ha⁻¹ yr⁻¹ at PTRS-14b.

¶ Average slope for the annual fertilizer-K rates 0 to 150 kg K ha⁻¹ yr⁻¹ at RREC-14 and 38 to 150 kg K ha⁻¹ yr⁻¹ at PTRS-14b.

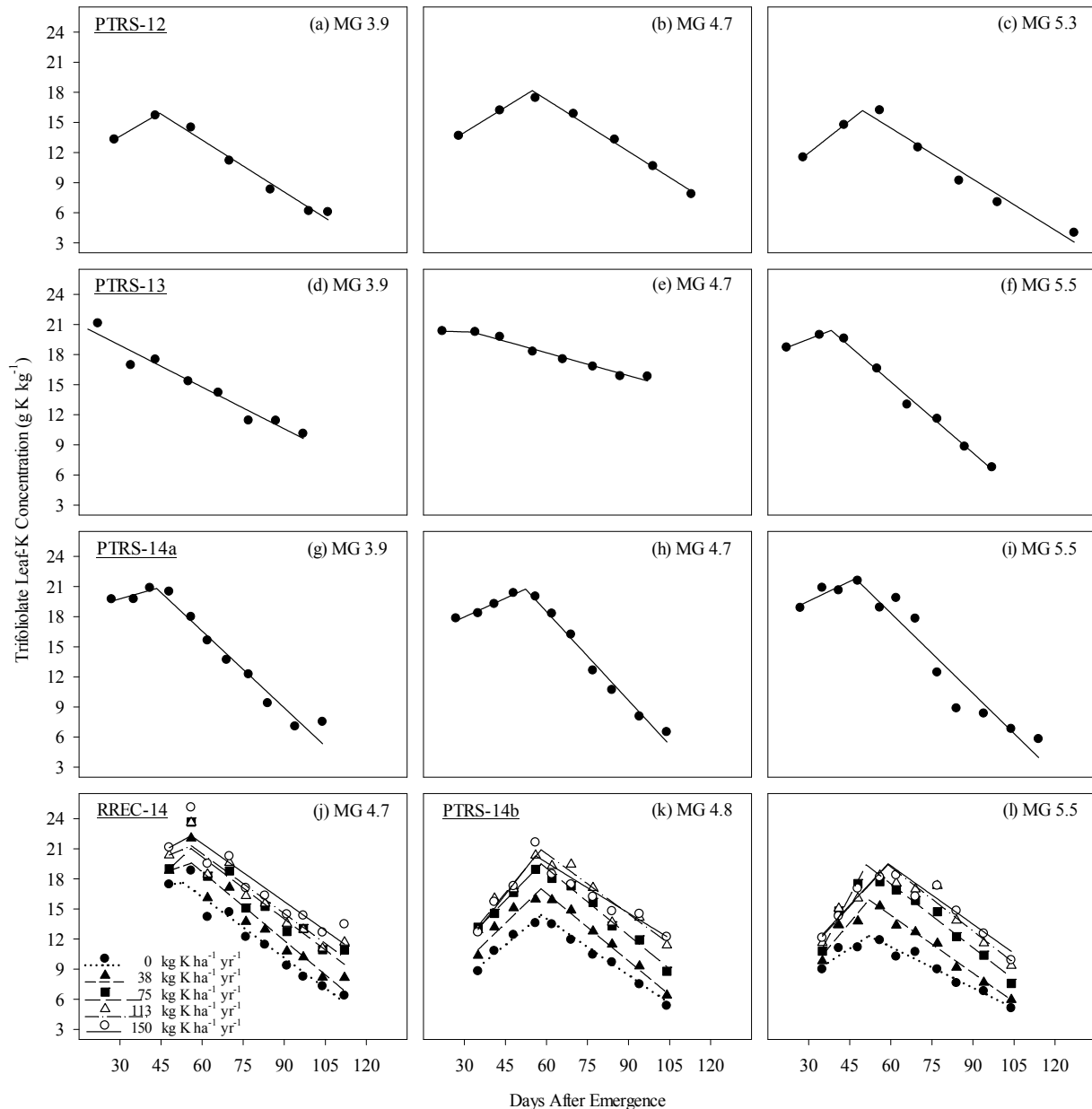


Fig. 5.1. Soybean trifoliolate leaf-K concentration change as a function of days after emergence as predicted with a linear-slope model for research trials conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12; a-c), 2013 (PTRS-13; d-f), and 2014 (PTRS-14a; g-i) with soybean cultivars representing three different maturity groups (MG) and for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14; j) and Pine Tree Research Station (PTRS-14b; k-l) in 2014 with five annual fertilizer-K rates and one or two soybean cultivars, respectively. Data for each trial were analyzed by cultivar and annual fertilizer-K rate. Model coefficients and time and growth stage where K concentration peaked are listed in Table 5.4.

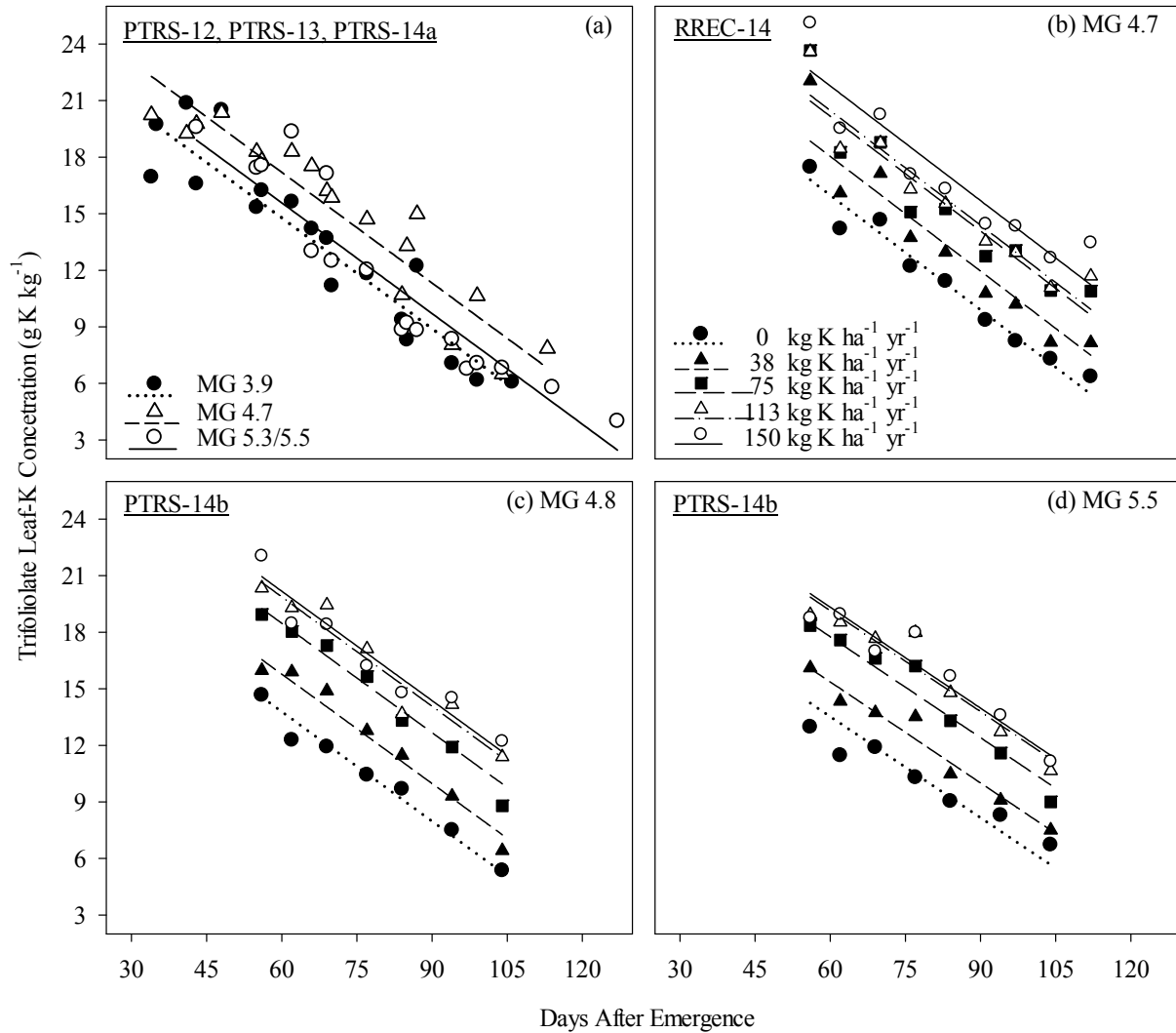


Fig. 5.2. Soybean trifoliolate leaf-K concentration change as a function of days after emergence from the growth stage where K concentrations peaked to the R6 or R7 stages as predicted with a linear model for research trials conducted at the Pine Tree Research Station (PTRS) in 2012 (PTRS-12; a-c), 2013 (PTRS-13; d-f), and 2014 (PTRS-14a; g-i) with soybean cultivars representing three different maturity groups (MG) and for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14; j) and Pine Tree Research Station (PTRS-14b; k-l) in 2014 with five annual fertilizer-K rates and one or two soybean MG cultivars, respectively. Data for each trial were analyzed by cultivar and annual fertilizer-K rate. Model coefficients are listed in Table 5.5. The growth stage of each cultivar of each trial that corresponded to a specific day after emergence is listed in Table 5.2.

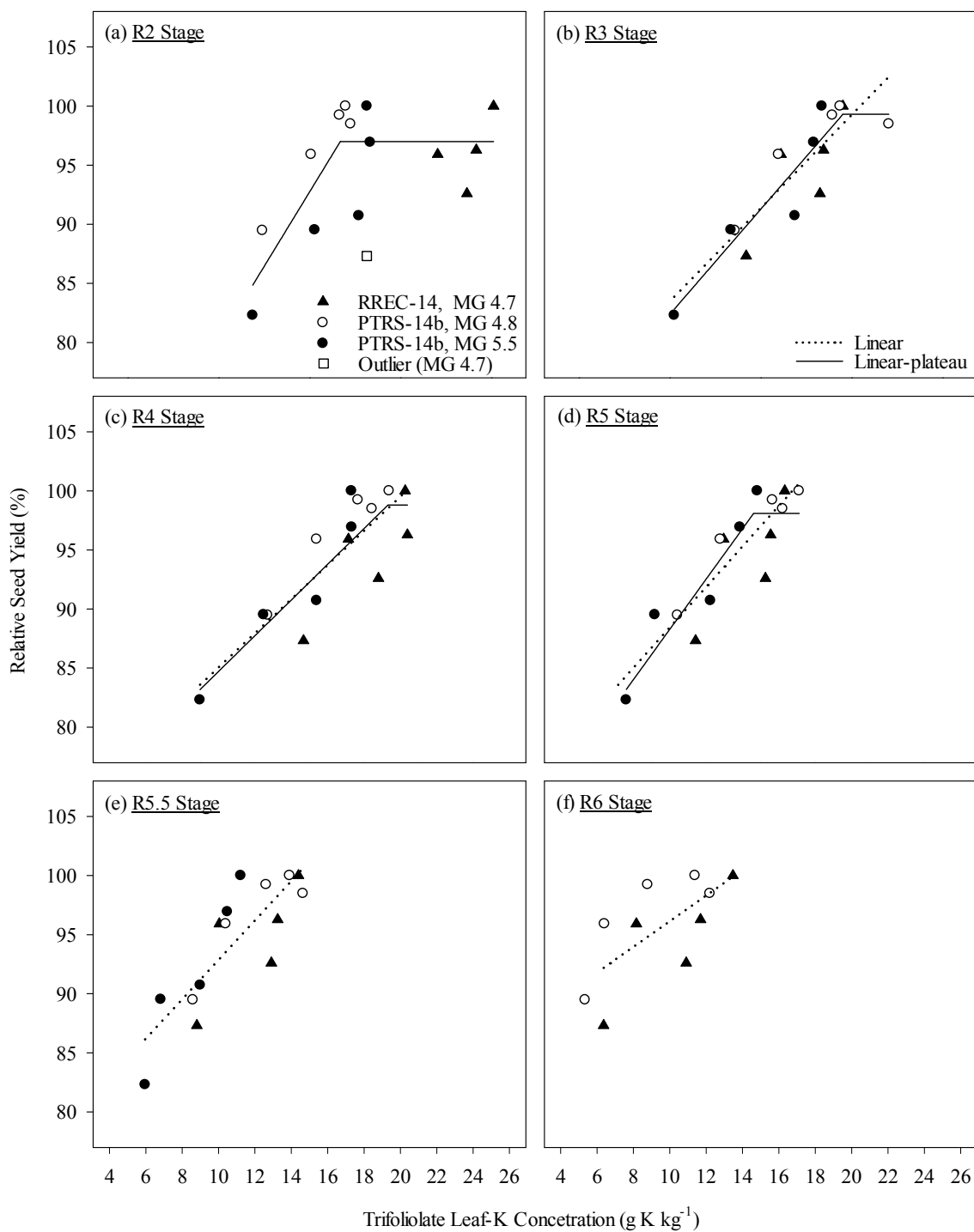


Fig. 5.3. Relationships between relative soybean seed yield and trifoliolate leaf-K concentration at the R2 (a), R3 (b), R4 (c), R5 (d), R5.5 (e), and R6 (f) stages for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) with a maturity group (MG) 4.7 cultivar and at the Pine Tree Research Station (PTRS-14b) with MG 4.8 and 5.5 cultivars in 2014. Mean data of each annual fertilizer-K rate for each cultivar and trial were used to model these relationships. Model coefficients are listed in Table 5.6.

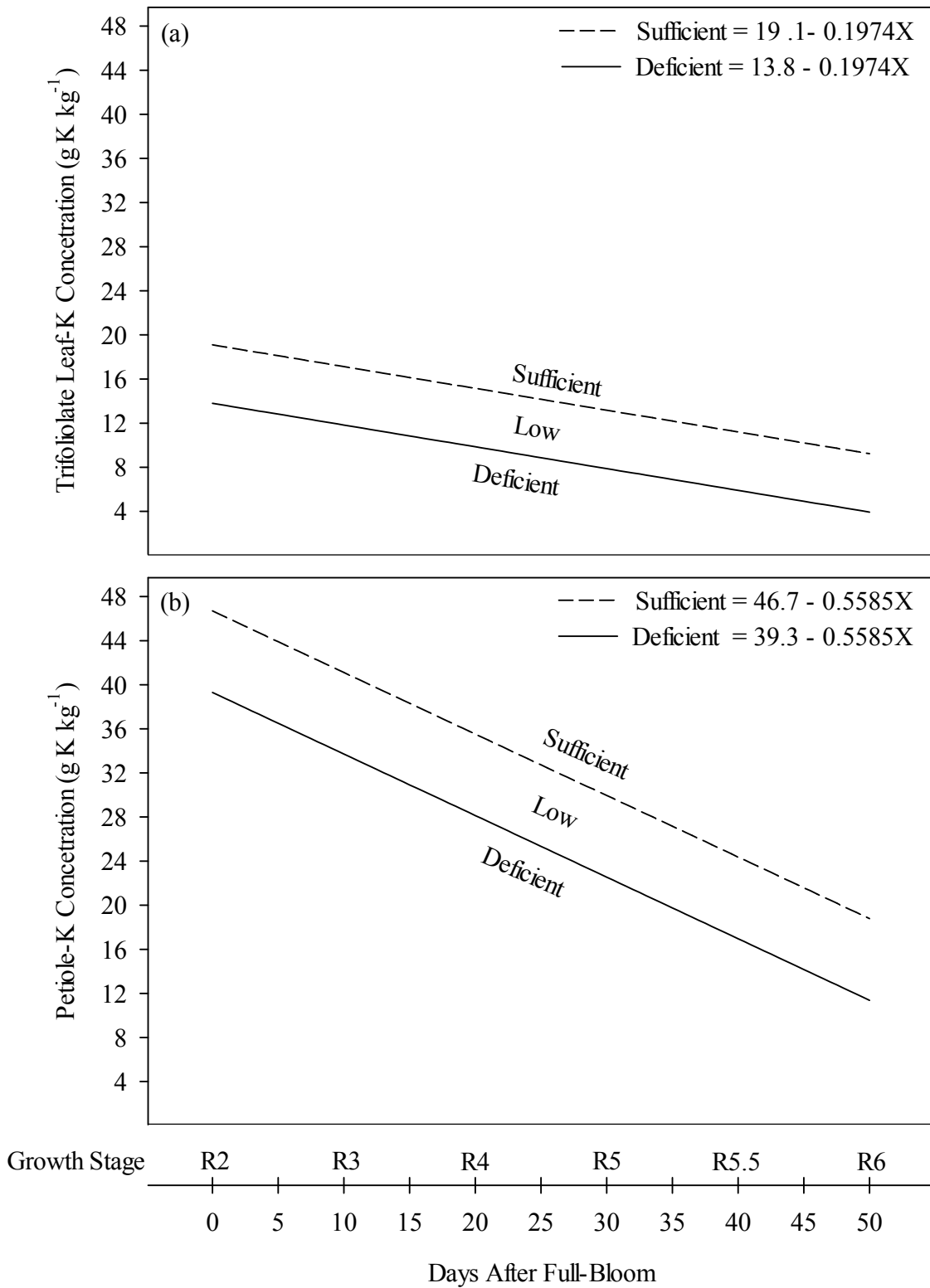


Fig. 5.4. Predicted soybean critical tissue-K concentrations across time in the trifoliolate leaves (a) and petioles (b) from the R2 (full-bloom) to R6 (full-seed) stages.

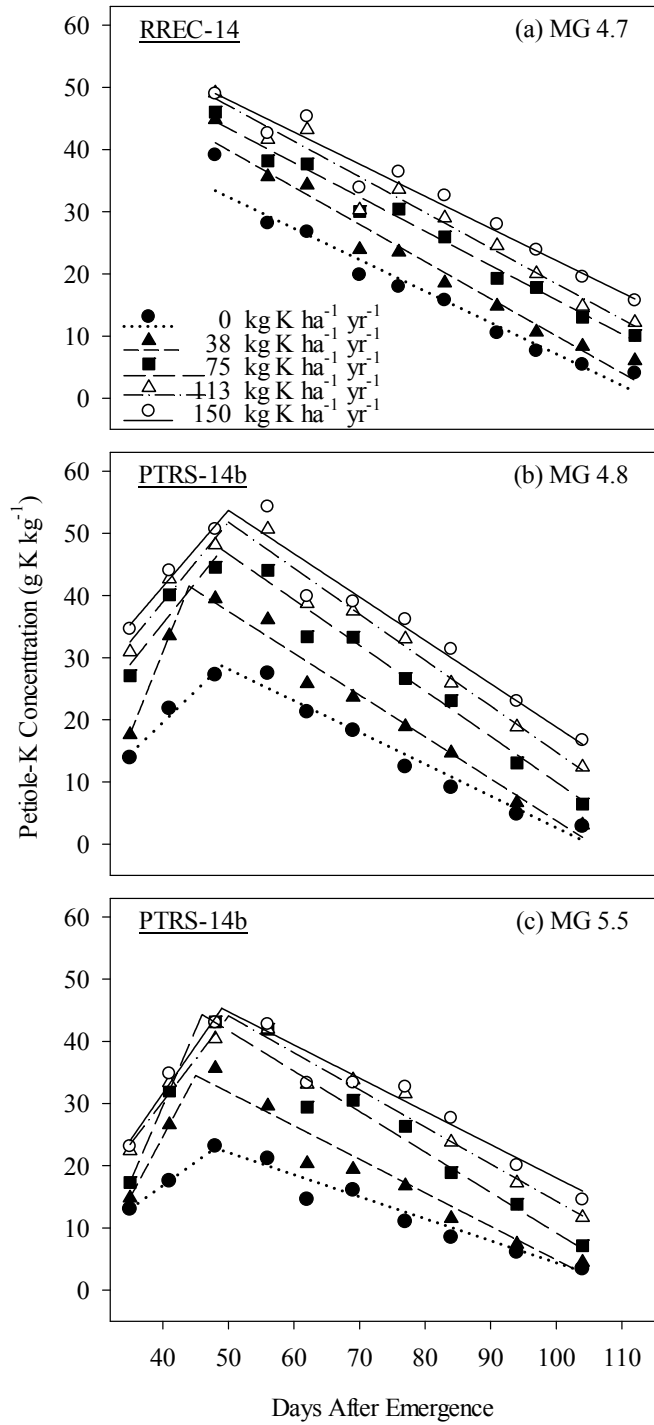


Fig. 5.5. Soybean petiole-K concentration change as a function of days after emergence as predicted with a linear-slope model for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14; j) and Pine Tree Research Station (PTRS-14b; k-l) in 2014 with five annual fertilizer-K rates and one or two soybean maturity groups (MG) cultivars, respectively. Data for each trial were analyzed by cultivar and annual fertilizer-K rate. Model coefficients and time and growth stage where K concentration peaked are listed in Table 5.4.

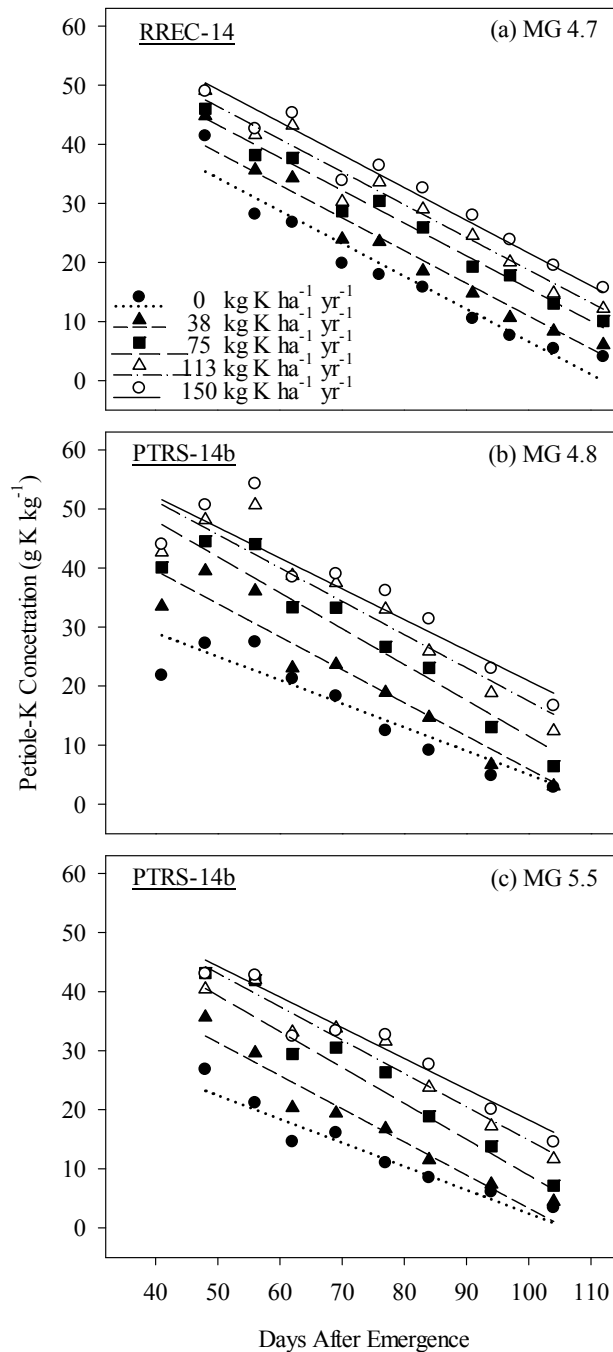


Fig. 5.6. Soybean petiole-K concentration change as a function of days after emergence from the growth stage where K concentrations peaked to the R6 or R7 stages as predicted with a linear model for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14; j) and Pine Tree Research Station (PTRS-14b; k-l) in 2014 with five annual fertilizer-K rates and one or two soybean maturity groups (MG) cultivars, respectively. Data for each trial were analyzed by cultivar and annual fertilizer-K rate. Model coefficients are listed in Table 5.7. The growth stage of each cultivar of each trial that corresponded to a specific day after emergence is listed in Table 5.2.

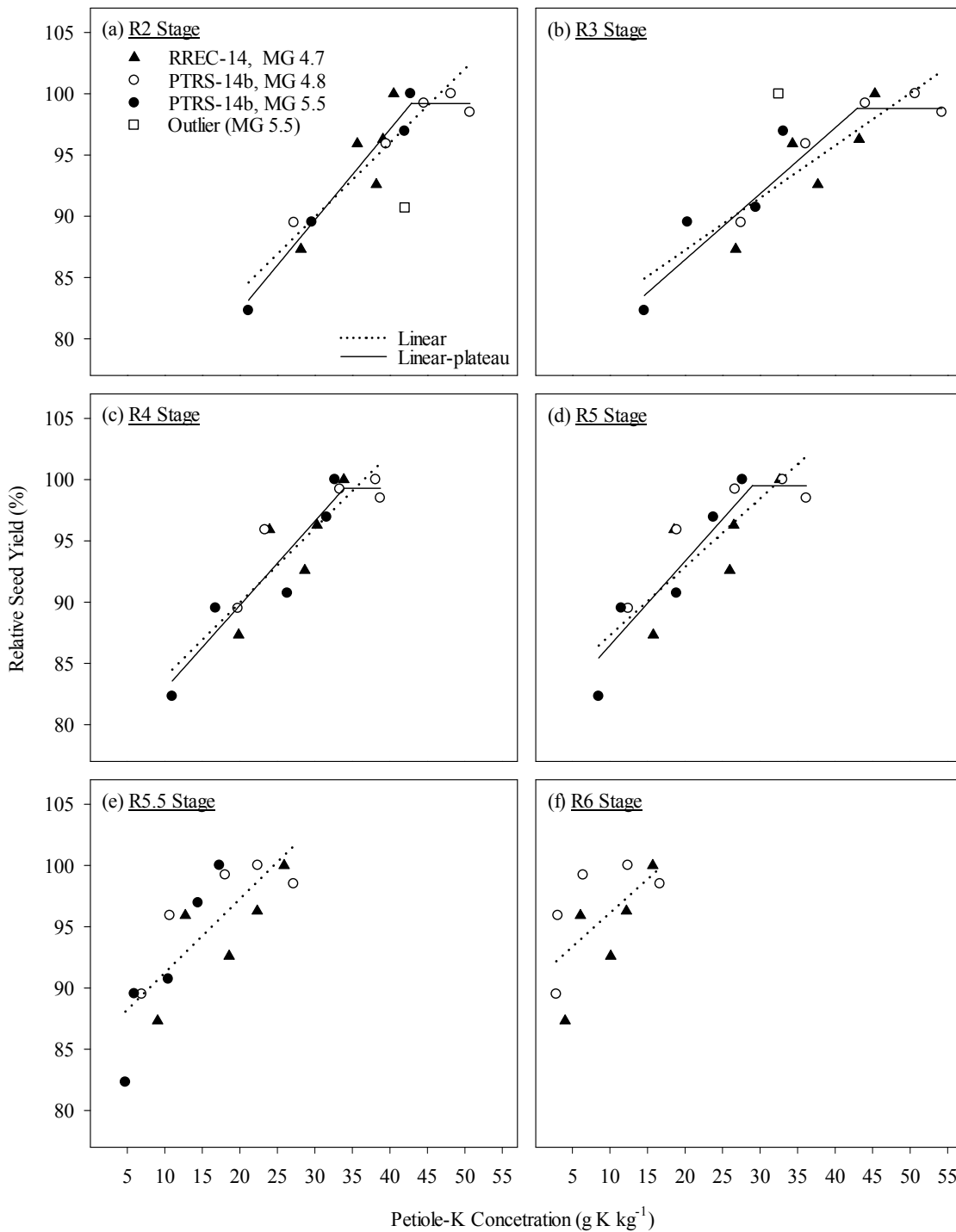


Fig. 5.7. Relationships between relative soybean seed yield and petiole-K concentration at the R2 (a), R3 (b), R4 (c), R5 (d), R5.5 (e), and R6 (f) stages for long-term K fertilization trials conducted at the Rice Research and Extension Center (RREC-14) with a maturity group (MG) 4.7 cultivar and at the Pine Tree Research Station (PTRS-14b) with MG 4.8 and 5.5 cultivars in 2014. Mean data of each annual fertilizer-K rate for each cultivar and trial were used to model these relationships. Model coefficients are listed in Table 5.6.

CHAPTER 6

Postseason Diagnosis of Potassium Deficiency in Soybean using Seed Potassium Concentration

ABSTRACT

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 concentration and soil-K availability and relative soybean yield and to develop potential seed-K concentration thresholds for diagnosis of K deficiency as a yield-limiting factor. Soil-K availability, seed-K concentrations and yield data were collected from published and unpublished K fertilization research conducted in Arkansas (33 site-years), Illinois (1), Iowa (34), Missouri (1), Tennessee (6), Virginia (1), and Canada (24). Seed-K concentration 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 100 sites in North America. The critical seed-K concentrations ranged from 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. Seed-K concentrations below the lower threshold (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 availability increased and plateaued when soil-K availability was ≥ 87 mg K kg⁻¹ for Arkansas, ≥ 139 mg K kg⁻¹ for Iowa, ≥ 73 mg K kg⁻¹ for Canada, and ≥ 104 mg K kg⁻¹ for North America. Results suggest that seed-K concentrations can be used to aid in the diagnosis of K deficiency at maturity.

INTRODUCTION

Potassium is a common yield-limiting nutrient for soybean production. Yield increases from K fertilization of 5 to 25% yield are common (Coale and Grove, 1990; Mallarino et al., 1991; Slaton et al., 2010, 2013; Clover and Mallarino, 2013; Parvej et al., 2015a), but soybean plants may not express K deficiency symptoms during the growing season. Trifoliolate leaf-K concentration at the R1-2 stage 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 since 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). Although K deficiency cannot likely be corrected at this late soybean 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 $\text{NO}_3\text{-N}$ concentration in a lower segment of mature corn (*Zea mays* L.) stalks is used to assess whether too little, enough, or too much 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. Small and Ohlrogge (1973) reported that soybean seed-K concentrations from 152 commercial fields was 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; Parker et al., 1981; Hitsuda et al., 2010), Zn (Hitsuda et al., 2010), B (Hitsuda et al., 2010), Cu (Hitsuda et al., 2010), and Mo (Lavy and Barber, 1963) deficiencies

can 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 $>2.3 \text{ g S kg}^{-1}$ 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 $>1.6 \text{ mg Mo kg}^{-1}$ 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-K availability with absolute corn grain-K concentration, but a significant relationship was found between relative grain-K concentration and soil-K availability. We could find no other research relating seed-K concentration to soil-K availability 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. Soybean seed-K concentrations 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, 1991; Terman, 1977; Yin and Vyn, 2002; Clover and Mallarino, 2013; Slaton et al., 2013; Parvej et al., 2015a). However, seed-K concentration increases from K fertilization in the absence of a yield benefit have also been reported (Clover and Mallarino, 2013; Slaton et al., 2013; Parvej et al., 2015a). Potassium fertilization can increase soybean seed-K concentrations more than 50% (Sale and Campbell, 1987), but increases of 5 to 20% are more typical (Vyn et al., 2002; Yin and Vyn, 2003; Nelson et al., 2005; Parsons et al., 2007; Bellaloui et al., 2013; Clover and Mallarino, 2013; Oltmans and Mallarino, 2015; Parvej et al., 2015a). 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 hypothesized that soybean relative seed yield and seed-K concentration would be positively correlated and that soybean seed could be used to diagnose K deficiency because research has shown soybean seed-K concentration is often influenced by 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 a total of 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 USA (Table 6.1). Among the 33 observations from Arkansas, twenty-five were from unpublished research. Only field research results were included in the dataset. Selected information including site number, geographic location [state (USA) or country of research], soil series, soil group, cultivar, previous crop, row spacing, and irrigation method, if available, for the 100 site-year results are summarized in Table 6.1. Seed-K concentration and soybean yield response to K fertilization 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 no fertilizer-K yield by the highest 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 actual yield than soybean receiving fertilizer-K and therefore could indicate a possible yield decrease from fertilization.

Information on soil pH, soil-K availability index, and yield and seed-K concentration responses to fertilizer-K are summarized in Table 6.2. The seed-K concentrations listed in Table 6.2 represents that of soybean receiving no fertilizer-K and the greatest numerical seed-K concentration of soybean receiving fertilizer-K. Soil chemical properties, including soil-K availability indices, were not listed for all site-years obtained from the literature. For site-years that had soil-K availability indices, soil-K was extracted with either the Mehlich-1 (Sims, 1989), Mehlich-3 (Helmke and Sparks, 1996), or NH_4OAc methods (Warncke and Brown, 1998) from air- or oven-dry soil samples that represented the 0-10 (Site 1-33, 73-89, and 98) or 0-15 (all other sites) cm soil depths prior to establishing the field trial. Soil-K availability indices determined only by the Mehlich-3 or NH_4OAc methods were used to evaluate the correlations between relative soybean yield and soil-K availability index and between seed-K concentration and soil-K availability index since these two extractants have consistently been shown to extract comparable amounts of soil-K (Beegle and Oravec, 1990) and 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 0-10 cm depth is, on average, 13 mg K kg^{-1} greater than in samples collected from the 0-15 cm depth (Slaton, unpublished data, 2007).

The amount of detail describing soybean seed analysis for each site-year obtained from the literature differs (see references listed in Table 6.1). In general, a subsample of harvested

seed was oven-dried, ground, seed or ash was digested, and 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 (v9.4, SAS Inst., Cary, NC). The LP model consistently had the lowest residual sums of squares and highest R^2 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 sites for Arkansas, 34 sites for Iowa, and 24 sites for Canada) and for all geographic locations grouped together (e.g., North America = 100 sites; Tables 6.1 and 6.2). The relationships between seed-K concentration and soil-K availability index and seed-K difference (seed-K of soybean that received fertilizer-K – seed-K of soybean that received no fertilizer-K) and soil-K availability index 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 residuals was $> \pm 2.5$ 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 as 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 plants 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 6.2; Fig. 6.1). The 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 omitted from the regression (Table 6.1 and 2). Soybean seed-K concentration accounted for 66% of the variability in relative yield among the 32 sites (Table 6.3; Fig. 6.1). Relative yield increased linearly as seed-K concentration increased and plateaued when the seed-K concentrations reached 16.3 g K kg⁻¹ (Table 6.3). 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 ≤ 15.5 g K kg⁻¹ were deficient and ≥ 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 6.4; Fig. 6.1). Among the 33 Arkansas sites, significant yield responses to fertilizer-K were measured at 14 of 15 sites with deficient seed-K concentrations, 4 of 9 sites with low seed-K, and 2 of 9 sites that had sufficient seed-K levels (Table 6.4). Likewise, 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 6.4).

Iowa

Non-irrigated soybean receiving no fertilizer-K at 34 sites in Iowa had relative yield of 83.4 to 121.4% and seed-K concentrations of 14.1 to 23.5 g K kg⁻¹ (Table 6.2; Fig. 6.2). The actual seed yields of soybean grown with and without fertilizer-K averaged 3698 and 3810 kg ha⁻¹, respectively, across the 34 sites. Site 65 was identified as an outlier and omitted from the dataset used to regress relative yield with seed-K concentration. Seed-K concentration explained 48% of the variability in relative yield among the Iowa sites (Table 6.3; Fig. 6.2). 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 6.4). Soybean having low seed-K concentrations responded positively to fertilizer-K at 28% of the sites but the average yield difference was only 2%. None of the sites within the sufficient seed-K level benefitted from fertilizer-K.

Canada

The overall seed yield across 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 6.2). Soybean receiving no fertilizer-K produced relative yields of 63.6 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. 6.3). The LP model, fit across 23 sites (Site 91 removed as an outlier), explained 78% of the variability in relative soybean yield (Table 6.3). 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 to that observed for Arkansas and slightly

better than defined for the Iowa sites (Table 6.4). 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 sites in 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 6.2; Fig. 6.4). Averaged across all 100 sites in North America, soybean receiving no fertilizer-K produced a mean yield of 3373 kg ha⁻¹ compared to 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, but three sites, one in Iowa (Site 65), one in Missouri (Site 99), and one in Virginia (Site 100) were identified as outliers, omitted from the dataset, and the model was refit. Soybean seed-K concentration accounted for 60% of the variability in relative yield (Table 6.3; Fig. 6.4). The critical seed-K concentration was 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 in identifying K responsive sites with 77% of the sites showing a significant yield benefit that averaged 485 kg ha⁻¹ (Table 6.4). Soybean having low or sufficient seed-K concentrations responded positively to fertilizer-K at 24% of the sites. Although the same percentage of sites classified as low and 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 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 6.4). 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 6.3).

The deficient seed-K level was reasonably accurate in predicting whether soybean responded positively to fertilizer-K with false positive errors occurring at 23% of the sites (Table 6.4) with no consistent error associated with seed-K concentrations from a specific region (2 in Arkansas, 0 in Canada, 5 in Iowa, and 1 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 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 negative errors are not evident, the errors could be associated with analytical errors or seed subsampling errors. Parvej et al. (2015b) 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 negative errors, the robust database makes the information more applicable across a wide geographic area.

Research has shown that soybean seed nutrient concentrations can be used to diagnose S, Mn, Zn, B, Cu, and Mo deficiencies (Lavy and Barber, 1963; Cox, 1968; Parker et al., 1981; Reinbott et al., 1997; Hitsuda et al., 2004, 2010; 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 Potassium 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 concentration and soil-K availability was performed in two separate evaluations using either the seed-K of soybean receiving no fertilizer-K (Fig. 6.5a) or soybean fertilized with K (Fig. 6.5b). The seed-K concentration of soybean receiving no fertilizer-K increased as soil-K availability increased linearly until 179 mg K kg⁻¹ and plateaued at 18.8 g K kg⁻¹ (Fig. 6.5a). Soil-K

availability explained 40% of the variability in seed-K. For soybean receiving fertilizer-K, seed-K concentration increased linearly until soil-K availability reached 170 mg K kg⁻¹ and plateaued at 19.1 g K kg⁻¹ (Fig. 6.5b). Soil-K availability 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 since 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 than zero or the entire model was not significant 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 concentration and soil-K availability (Mallarino and Higashi, 2009).

The relationships between seed-K concentration and soil-K availability suggested that fertilizer- and soil-K availability both influence soybean seed-K concentration when soil-K availability is <170-179 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-K availability index (Table 6.5; Fig. 6.6). The relationship was significant for each of the four geographic locations (Table 6.5) and showed that the difference in seed-K concentration decreased as soil-K availability increased with seed-K difference plateauing when soil-K availability was ≥ 87 mg K kg⁻¹ for Arkansas (Fig. 6.6a), ≥ 139 mg K kg⁻¹ for Iowa (Fig. 6.6b), ≥ 73 mg K kg⁻¹ for Canada (Fig. 6.6c), and ≥ 104 mg K kg⁻¹ for North America (Fig. 6.6d). As with the relationship between seed-K and relative yield, specific reasons for the different critical soil-K availability index 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, 2012). Drying soil before extraction can significantly increase the soil-K index. 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 (Luebs et al., 1956). This phenomena may be responsible for many of the false negative and positive yield responses observed, especially for soils that had a relatively high soil-K availability index.

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 hypothesis and showed that soybean seed-K concentration explained 48-78% 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 16.5-17.7 g K kg⁻¹ when data from all the sites 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 influence soybean seed-K concentration, but only when soil-K availability was <170-179 mg K kg⁻¹. Although seed analysis is not helpful for identifying and correcting K deficiency during the growing season, as a postharvest tool it may be of value for diagnosing potential reasons for lower than expected yields and correcting K deficiency for subsequent crops.

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Table 6.1. Selected soil and agronomic information of each site.

Site	Location	Soil classification		Cultivar	Previous crop	Row spacing	Irrigation	References
		Series	Group†					
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 (Unpublished data, 2015)
11	Arkansas	Sharkey/Desha	CE/VH	Armor 55R22	Soybean	97	Irrigated	Fryer (Unpublished data, 2015)
12	Arkansas	Desha	VH	Armor 55R22	Soybean	97	Irrigated	Fryer (Unpublished data, 2015)
13	Arkansas	Foley/Calhoun	GN/TG	Armor X1307	Rice	38	Irrigated	Fryer (Unpublished data, 2015)
14	Arkansas	Sharkey/Steele	CE/AU	Armor X1307	Soybean	97	Irrigated	Fryer (Unpublished data, 2015)
15	Arkansas	Calloway	AF	Armor 48R40	Soybean	38	Irrigated	Fryer (Unpublished data, 2015)
16	Arkansas	Calloway	AF	Armor X1316	Soybean	38	Irrigated	Fryer (Unpublished data, 2015)
17	Arkansas	Calloway	AF	Armor X1307	Rice	38	Irrigated	Fryer (Unpublished data, 2015)
18	Arkansas	Dewitt	TA	Armor 47R13	Soybean	76	Irrigated	Fryer (Unpublished data, 2015)
19	Arkansas	Sharkey/Desha	CE/VH	Armor 55R22	Soybean	97	Irrigated	Fryer (Unpublished data, 2015)
20	Arkansas	Sharkey/Desha	CE/VH	Armor 55R22	Soybean	97	Irrigated	Fryer (Unpublished data, 2015)
21	Arkansas	Sharkey	CE	Halo 4:99	Soybean	97	Irrigated	Fryer (Unpublished data, 2015)
22	Arkansas	Calloway	AF	Armor 55R22	Soybean	38	Irrigated	Fryer (Unpublished data, 2015)
23	Arkansas	Calloway	AF	Armor 55R22	Soybean	38	Irrigated	Fryer (Unpublished data, 2015)
24	Arkansas	Calloway	AF	Pioneer 94Y82	Soybean	76	Irrigated	Fryer (Unpublished data, 2015)
25	Arkansas	Calloway	AF	Armor 49R56	Soybean	38	Irrigated	Fryer (Unpublished data, 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)

Table 6.1. (Cont.)

Site	Location	Soil classification		Cultivar	Previous crop	Row spacing	Irrigation	References
		Series	Group†					
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)
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)

Table 6.1. (Cont.)

Site	Location	Soil classification		Cultivar	Previous crop	Row spacing	Irrigation	References
		Series	Group†					
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)

Table 6.1. (Cont.)

Site	Location	Soil classification		Cultivar	Previous crop	Row spacing	Irrigation	References
		Series	Group†					
97	Tennessee	Dexter	-	Pioneer 94M80	Soybean	76	Rainfed	Bellaloui et al. (2013)
98	Illinois	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 Argiudolls; AF, Aquic Fraglossudalfs; AH, Aquic Hapludolls; APH, Aquic Pachic Hapludolls; ATA, Aquertic Argiudolls; AU, Aquic Udifluvents; CE, Chromic Epiaquerts; GN, Glossic Natraqualfs; RK, Rhodic Kandiudults; TA, Typic Albaqualfs; TE, Typic Endoaquolls; TF, Typic Fragiaqualfs; TG, Typic Glossaqualfs; TH, Typic Hapludolls; UEN, Udollic Endoaqualf; UEP, Udollic Epiaqualf; VA, Vertic Argiaquolls; VE, Vertic Epiaqualfs; VH, Vertic Hapludolls.

Table 6.2. Selected soil chemical property and relative seed yield (RSY) means of soybean that received no fertilizer-K (No K) and actual yield and seed-K concentration means of soybean as affected by K fertilization for each site.

Site†	Soil pH	Soil-K		Seed yield			Seed-K concentration		
		concentration‡§ mg K kg ⁻¹	RSY¶ %	No K	+K#	Response††	No K	+K#	Response††
				-----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

Table 6.2. (Cont.)

Site†	Soil pH	Soil-K	RSY¶	Seed yield			Seed-K concentration		
		concentration‡§ mg K kg ⁻¹		%	No K	+K#	Response††	No K	+K#
				-----kg ha ⁻¹ -----			-----g K kg ⁻¹ -----		
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
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

Table 6.2. (Cont.)

Site†	Soil pH	Soil-K concentration‡§ mg K kg ⁻¹	RSY¶ %	Seed yield			Seed-K concentration		
				No K	+K#	Response††	No K	+K#	Response††
				-----kg ha ⁻¹ -----		-----g K kg ⁻¹ -----			
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

Table 6.2. (Cont.)

Site†	Soil pH	Soil-K concentration‡§ mg K kg ⁻¹	RSY¶ %	Seed yield			Seed-K concentration		
				No K	+K#	Response††	No K	+K#	Response††
				-----kg ha ⁻¹ -----			-----g K kg ⁻¹ -----		
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 6.1.

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

§ Soil-test K was extracted by Mehlich-3 for Site 1-33 and 90-91, NH₄OAc for Site 34-89 and 98-99, and Mehlich-1 for Site 92-97 and 100, but no soil-test K information for Site 95-97 was provided.

¶ Relative yield of the no K-fertilized plants 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 Site 1-67 and 0.05 probability level for Site 68-100.

Table 6.3. Relationship between soybean seed-K concentration (SKC) and relative seed yield (RSY) as predicted with 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 -----	
				<u>Arkansas</u>			
LP	-10.3	6.552	0.66	16.3	96.5	15.6	17.0
SE	17.6	1.172	-	0.4	4.6	-	-
				<u>Iowa</u>			
LP	34.6	3.427	0.48	18.7	98.6	17.4	20.0
SE	15.0	0.874	-	0.6	4.5	-	-
				<u>Canada</u>			
LP	-35.0	8.565	0.78	15.4	97.0	14.6	16.2
SE	25.8	1.849	-	0.4	4.1	-	-
				<u>North America</u>			
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 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 as deficient and greater than the upper CL threshold were considered as sufficient. Seed-K concentrations within the CL were considered as low.

Table 6.4. 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 6.3).

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

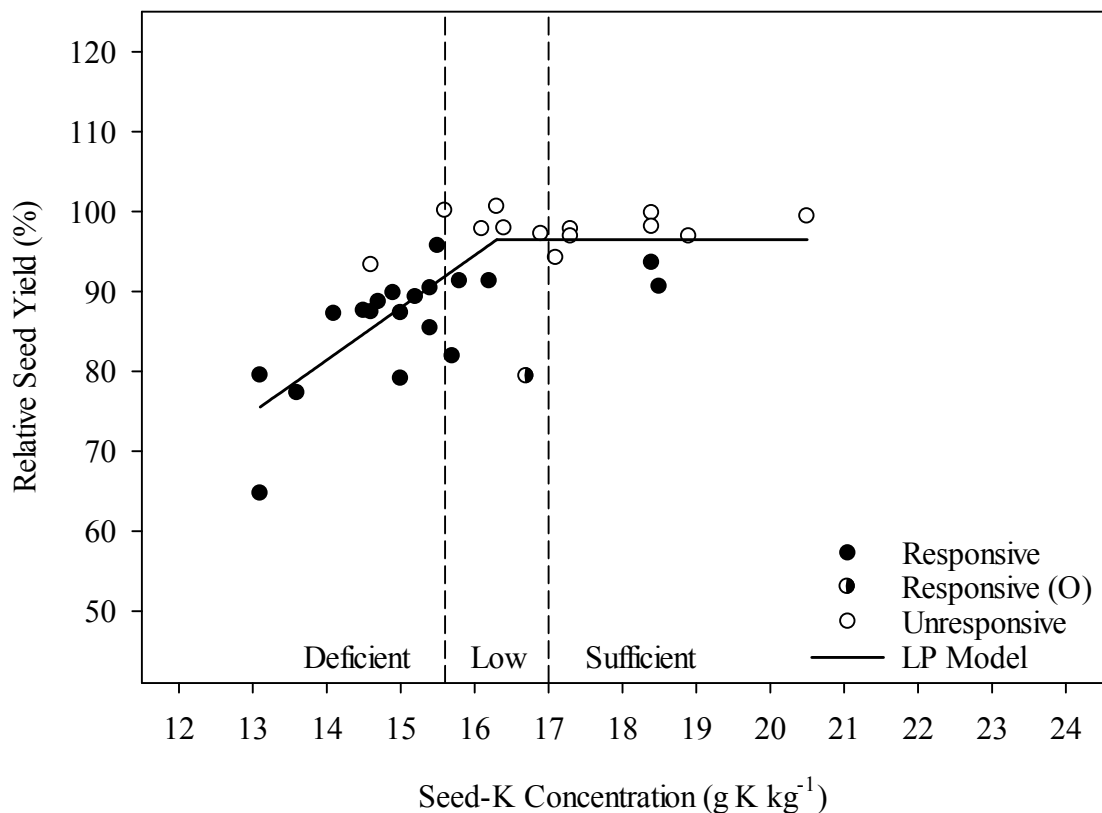


Fig. 6.1. Relationship between relative soybean yield and seed-K concentration as predicted with linear-plateau (LP) model across 33 sites in Arkansas. Responsive or unresponsive indicates whether or not soybean seed yield was significantly increased by fertilizer-K at the 0.10 probability level and is shown for Site 1-33 in Table 6.2. Site 4 [Responsive (O)] was identified as an outlier and omitted from the statistical analysis. The two vertical dashed lines indicate the critical or low seed-K concentrations thresholds. The LP model coefficients and the low seed-K concentrations thresholds are listed in Table 6.3.

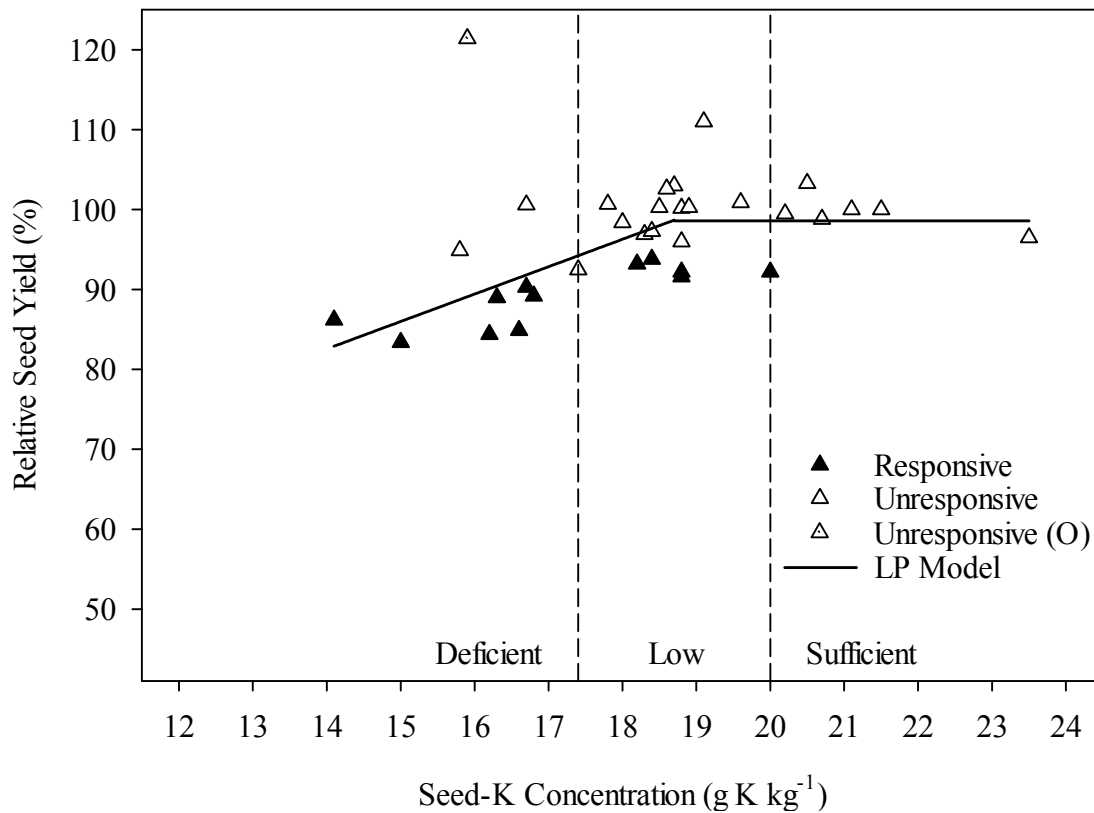


Fig. 6.2. Relationship between relative soybean yield and seed-K concentration as predicted with linear-plateau (LP) model across 34 sites in Iowa. Responsive or unresponsive indicates whether or not soybean seed yield was significantly increased by fertilizer-K at the 0.10 probability level and is shown for Site 34-67 in Table 6.2. Site 65 [Unresponsive (O)] was identified as an outlier and omitted from the statistical analysis. The two vertical dashed lines indicate the critical or low seed-K concentrations thresholds. The LP model coefficients and the low seed-K concentrations thresholds are listed in Table 6.3.

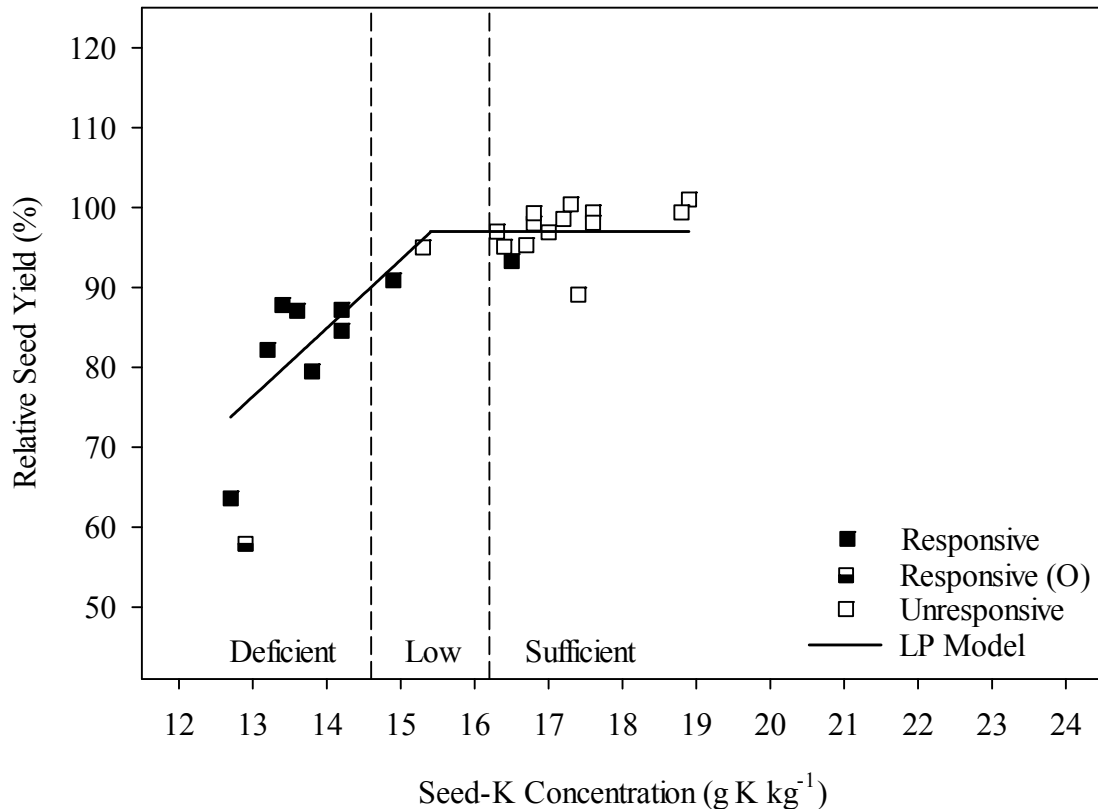


Fig. 6.3. Relationship between relative soybean yield and seed-K concentration as predicted with linear-plateau (LP) model across 24 sites in Ontario, Canada. Responsive or unresponsive indicates whether or not soybean seed yield was significantly increased by fertilizer-K at the 0.05 probability level and is shown for Site 68-91 in Table 6.2. Site 91 [Responsive (O)] was identified as an outlier and omitted from the statistical analysis. The two vertical dashed lines indicate the critical or low seed-K concentrations thresholds. The LP model coefficients and the low seed-K concentrations thresholds are listed in Table 6.3.

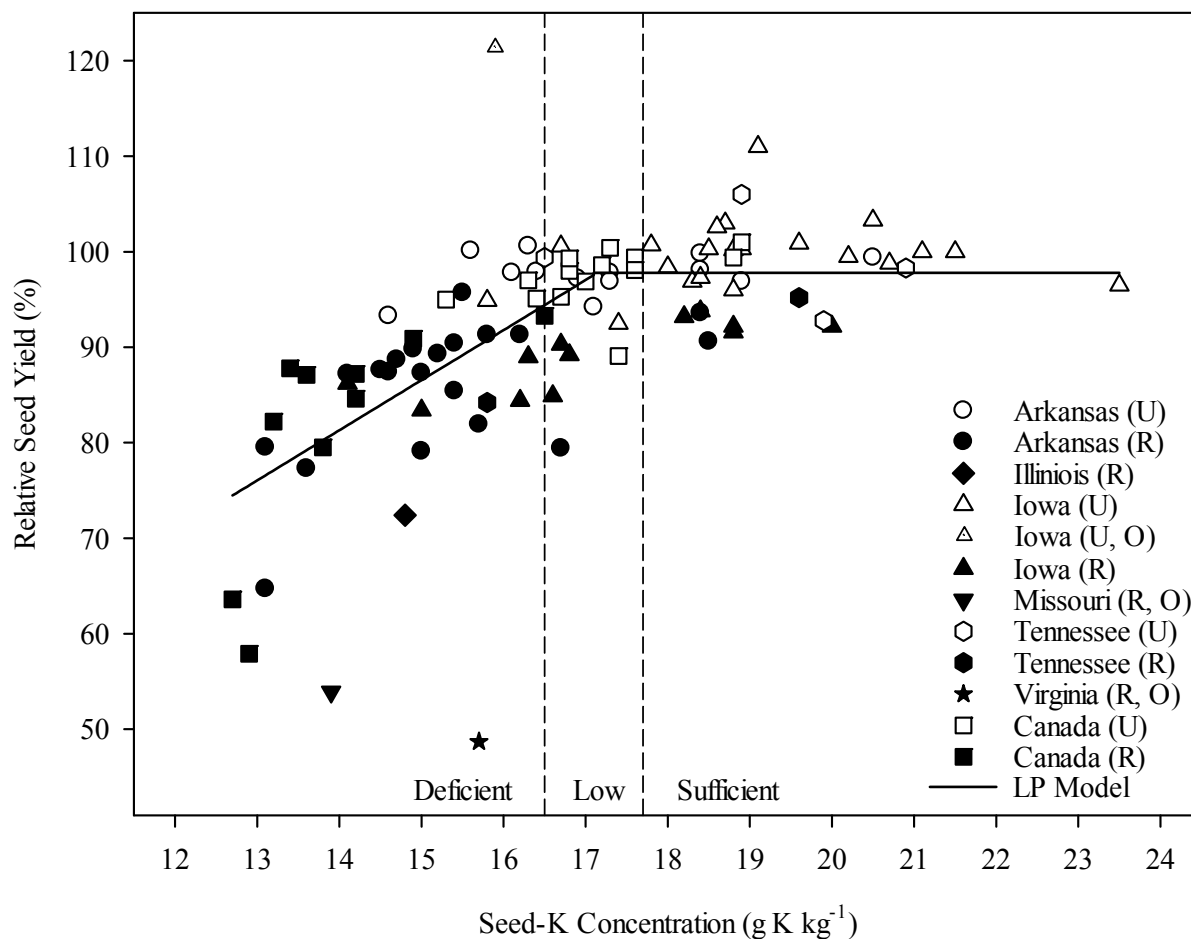


Fig. 6.4. Relationship between relative soybean yield and seed-K concentration as predicted with linear-plateau (LP) model across 100 sites in North America. Responsive (R) or unresponsive (U) indicates whether or not soybean seed yield was significantly increased by fertilizer-K at the 0.10 probability level for Site 1-67 and 0.05 probability level for Site 68-100 and are shown in Table 6.2. Site 65 [Iowa (U, O)], 99 [Missouri (R, O)], and 100 [Virginia (R, O)] were identified as outliers and omitted from the statistical analysis. The two vertical dashed lines indicate the critical or low seed-K concentrations thresholds. The LP model coefficients and the low seed-K concentrations thresholds are listed in Table 6.3.

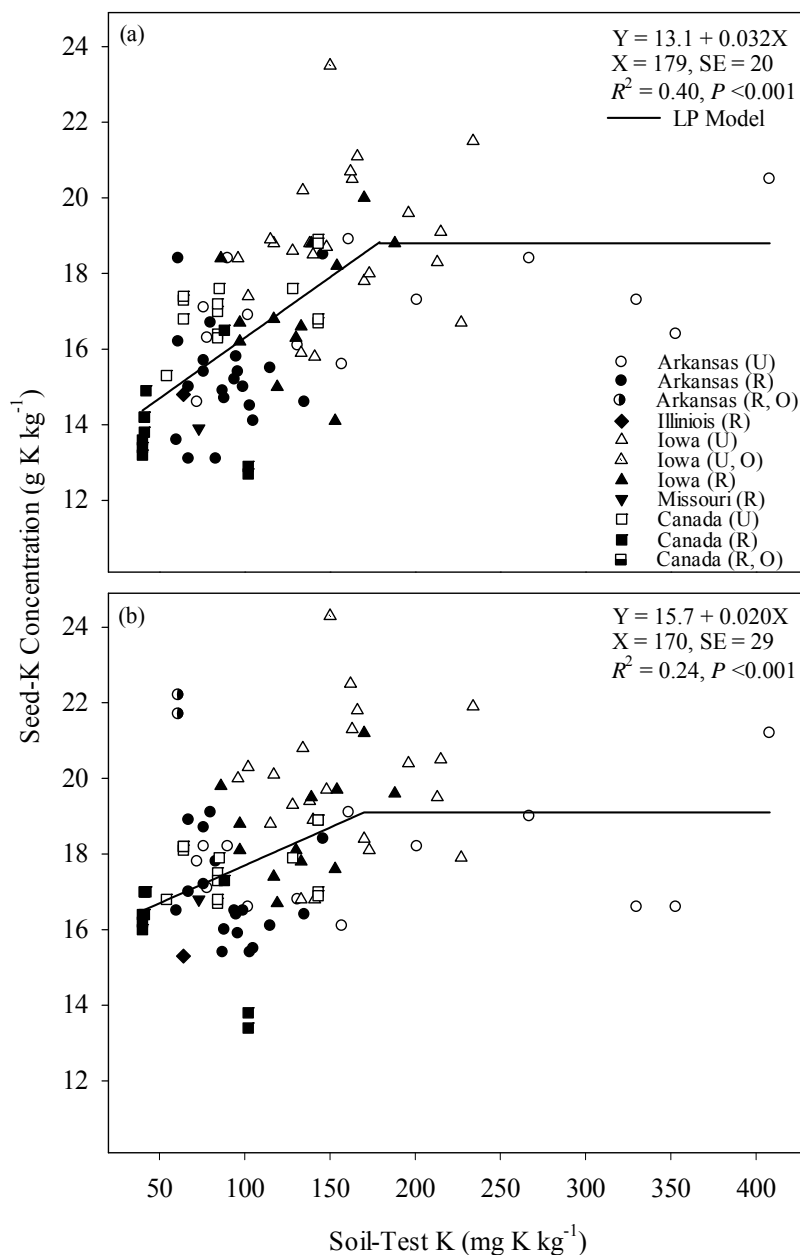


Fig. 6.5. Relationships between seed-K concentrations of no K-fertilized soybean (a) and K-fertilized soybean (b) and soil-K availability indices as predicted with a linear-plateau (LP) model across 93 sites (Site 1-91 and 98-99) in North America. Responsive (R) or unresponsive (U) indicates whether or not soybean seed yield was significantly increased by fertilizer-K at the 0.10 probability level for Site 1-67 and 0.05 probability level for Site 68-100 and are shown in Table 6.2. 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 1-33, 90-91, and 99, by NH_4OAc for Sites 34-89 and 98, and by Mehlich-1 for Sites 92-97 and 100 (Table 6.2). Sites located in Tennessee (Site 92-97) and Virginia (Site 100) used Mehlich-1 and were omitted from the regression.

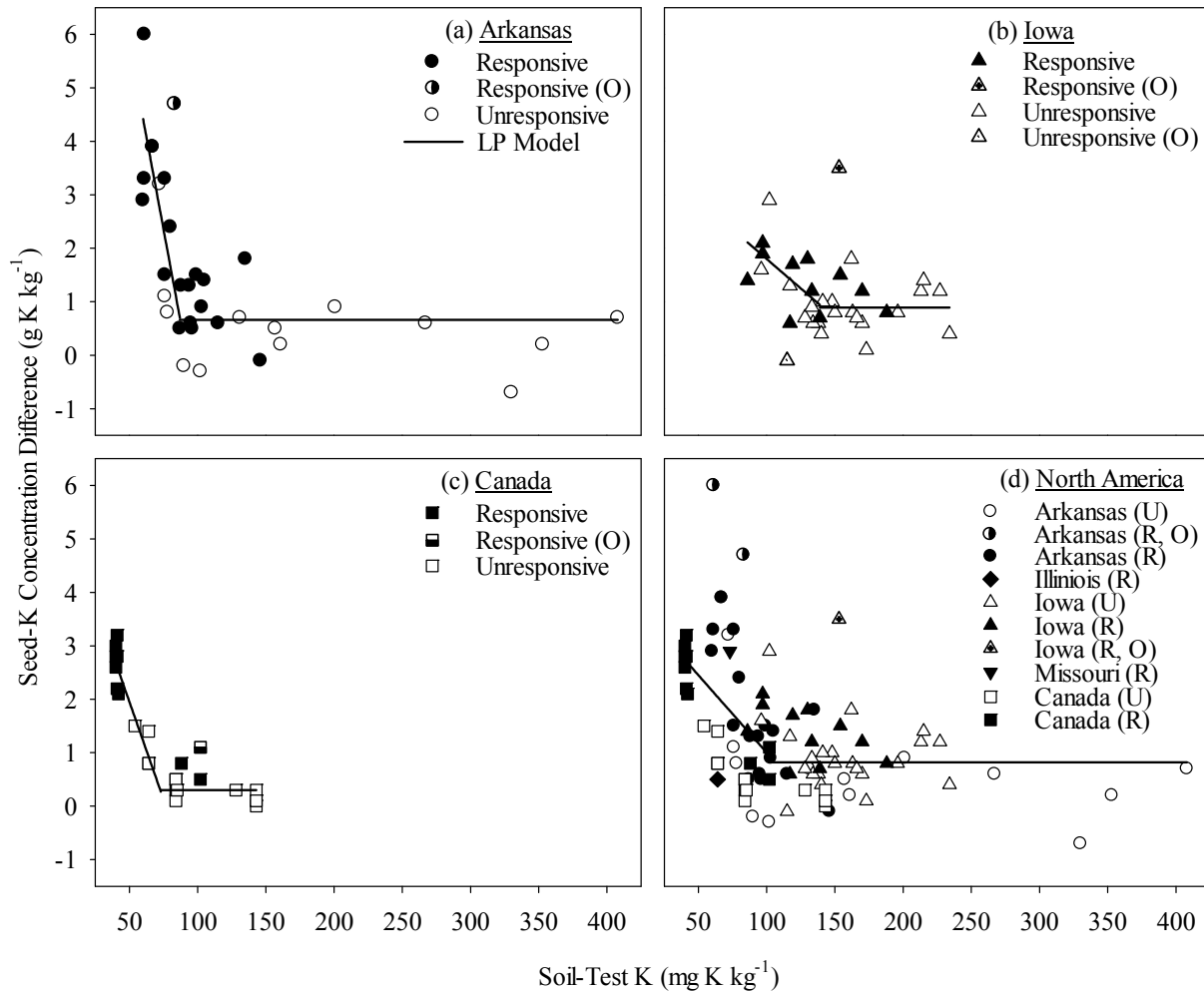


Fig. 6.6. Relationships between soybean seed-K concentration difference (seed-K with fertilizer-K – seed-K without fertilizer-K) and soil-K availability index as predicted with a linear-plateau (LP) model across 33 sites (Site 1-33) in Arkansas (a), 34 sites (Site 34-67) in Iowa (b), 24 sites (Site 68-91) in Ontario, Canada (c), and 93 sites (Site 1-91 and 98-99) in North America (d). 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 Site 1-67 and 0.05 probability level for Site 68-100 and is shown in Table 6.2. 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 Site 1-33, 90-91, and 99, by NH_4OAc for Site 34-89 and 98, and by Mehlich-1 for Site 92-97 and 100 (Table 6.2). Sites located in Tennessee (Site 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 6.5.

CHAPTER 7

Conclusions

Potassium is a common yield-limiting nutrient for soybean production. The growth differences between determinate and indeterminate soybean cultivars suggest that their response to K deficiency could be different. The primary questions addressed by our research were i) does K deficiency influence yield and yield components of determinate and indeterminate soybean the same and ii) how does K deficiency influence the distribution of seed yield and seed-K concentration among nodes of determinate and indeterminate soybean? Both determinate and indeterminate soybean responded similarly to K deficiency in regards to their individual seed weight, pod and seed numbers, seed abortion, and seed yield. The yield loss from K deficiency was greatest on the nodes that produced the largest proportion of seed yield for each growth habit, which included nodes on the top two-thirds of the indeterminate cultivar and the top one-half of nodes plus the bottom nodes for the determinate cultivar. The rapid decline of seed-K concentration from the bottom to the top nodes of K-deficient soybean compared to K-sufficient soybean helped explain why K deficiency symptoms commonly appear on the middle and upper canopy during reproductive growth and might be useful in diagnosing K deficiency at maturity in fields that showed no visible K deficiency symptoms (i.e., hidden hunger).

Understanding how K is accumulated and distributed among aboveground plant parts of determinate and indeterminate soybean is required to develop sound fertilization programs and diagnostic information to assess plant nutritional health. The objective of this research was to characterize aboveground biomass and K uptake of representative cultivars from the maturity groups (MG) grown in Arkansas. Our experiment showed that K accumulation for MG 3.9 (indeterminate), 4.7 (indeterminate) and 5.3/5.5 (determinate) cultivars peaked at the R5.5-6.0 stage with the maximum K accumulation rate at the R3-4 stage. The MG 3.9 and 4.7 cultivars had higher K accumulation rates than the MG 5.5 cultivar during the early reproductive stages

(R1-4), but these differences in K accumulation rates did not affect K partitioning, mobilization, and seed yield among cultivars. The pattern of K accumulation suggests that K deficiency of soybean could possibly be corrected by timely fertilization during early reproductive growth with little or no yield loss. However, proper diagnosis is first required to correct K deficiency during the growing season.

Trifoliolate leaf-K concentration at the R1-2 stage is currently the only information available to diagnose in-season K deficiency. The research objective was to develop critical tissue-K thresholds for diagnosis of K deficiency throughout the reproductive growth phase. Both trifoliolate leaf- and petiole-K concentrations from the R2 to R5.5 stages were highly correlated with the relative soybean yield. Trifoliolate leaf- and petiole-K concentrations both peaked around the R2 stage and then declined linearly at a constant rate, regardless of soybean cultivar, growth habit, or annual fertilizer-K rate. Because tissue-K concentrations decline at a constant rate, critical tissue-K concentrations can be extended to interpret tissue-K concentrations at growth stages beyond R2. Compared to trifoliolate leaf-K concentrations, petiole-K concentrations were approximately two-fold greater with a nearly threefold greater linear decline rate across the reproductive stages, which may allow for more accurate separation of the deficient- and sufficient-K concentrations within a growth stage, as well as between growth stages. Soybean petioles may be an equally good or perhaps better tissue than trifoliolate leaves for monitoring the K nutritional status of soybean during reproductive growth. This result would enable agricultural practitioners to monitor the K nutritional status of soybean across a range of growth stages.

Seed analysis might be a useful postharvest tool for diagnosing potential reasons for lower than expected yields and diagnosing K deficiency as a possible reason. A dataset of seed-K

concentrations from 100 K fertilization trials conducted across North America showed that relative soybean seed yield and seed-K concentration were highly correlated. Seed having K concentrations $<16.5 \text{ g K kg}^{-1}$ were identified as K-deficient and the threshold accurately (77% of field sites) predicted that yield responded positively and significantly to K fertilization. Results confirm that seed-K concentrations can be used to diagnose K deficiency of soybean at maturity.