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Macro-Nutrient Concentration and Content of Irrigated Soybean Grown in the Early Production System of the Midsouth

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ABSTRACT

Macro-nutrients in soybean (Glycine max L. Merr.) have not been extensively researched recently. Concentrations and contents of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (N, P, K, Ca, Mg, and S) were determined for three irrigated cultivars grown using the early soybean production system (ESPS) on two soils (a sandy loam and a clay) in the Mississippi Delta during 2011 and 2012. Data were collected at growth stages V3, R2, R4, R6, and R8. No change in macro-nutrients due to soil type or years occurred and modern cultivars were similar to data collected >50 years ago. Mean seed yield of 3328 kg ha\(^{-1}\) removed 194.7 kg N ha\(^{-1}\), 16.5 kg P ha\(^{-1}\), 86.0 kg K ha\(^{-1}\), 17.5 kg Ca ha\(^{-1}\), 9.0 kg Mg ha\(^{-1}\), and 10.4 kg S ha\(^{-1}\). Increased yields over the decades are likely due to changed plant architecture and/or pests resistance, improved cultural practices, chemical weed control, and increased levels of atmospheric carbon dioxide (CO\(_2\)). Yield improvements by genetically manipulating nutrient uptake appear to be unlikely.

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KEYWORDS

Macro-nutrients; nutritional requirements; soybean

Introduction

Nutritional requirements of crops have always been of interest but, more so now than before because of changing economic and environmental dynamics in crop production. Increased demands for limited water supplies for uses other than agriculture along with the resulting depletion of non-renewable water resources, higher energy and fertilizer costs, adoption of genetically modified crops, and climate change (Allen et al. 2012), alter the landscape of crop production. Concerns over agriculture’s contribution to increased water consumption and its possible contamination of water resources sources through current production practices also stimulate a need for more current information about the nutrient requirements of most of our agronomic crops.

Recently, Bender, Haegele, and Below (2015) reported on an extensive study of biomass production and nutrient uptake of two Maturity Group (MG) 2.8 and one Mg 3.4 soybean cultivars grown on glacial formed soils near 40° N and 42° N latitude. They concluded that supplemental fertility had a modest effect on increasing biomass and yield but none on nutrient portioning. Prior to this study, Ohlrogge’s (1960) extensive review of available literature prior to 1960 on the uptake of essential nutrients by soybean was considered the primary source of nutrient uptake information on that crop. He stated with respect to nitrogen (N) that daily uptake of available soil N plus symbiotic N, acquired via fixation by Bradyrhizobium japonicum, consistently increased to a peak of approximately 5.3 kg N ha\(^{-1}\) d\(^{-1}\) 90 d after seeding and then began rapidly falling off. Lathwell and Evans (1951) stated that soybean yield was closely correlated with the N accumulated throughout the season. They concluded that seed yield was mainly determined by pods per plant which was determined by N availability during the bloom period. Though much of the N uptake by soybean is from symbiosis, it can range from 25% to 75% of the total N required, depending upon available
soil moisture (Zapata et al. 1987). Allos and Bartholomew (1959) had reported earlier that only 50%–75% of the total N required for maximum yields could be supplied by symbiotic fixation. Added N fertilizer though has had mixed results with no increase in seed yields being reported in some studies (Long et al. 1965; Maples and Keogh 1969) and increases in yield in others (Brevedan, Egli, and Leggett 1978; Pettiet 1971).

Research on phosphorus (P) in soybean has demonstrated the most common levels of the element found in field grown plants to be between 2.5 and 3.0 mg g\(^{-1}\) dry weight (Ohlrogge 1960). Mederski (1950) found in plants grown outdoors in a sand-nutrient culture system that the mean P level of the top growth 30 d after seeding was 6.5 mg g\(^{-1}\) of the total dry weight. Later, at 6 d pre-bloom, the mean total P content was 10.5 mg g\(^{-1}\). Hammond, Black, and Norman (1951) reported shortly thereafter that at maturity between 82% and 85% of the P taken up by a soybean plant will be contained in the seed.

Soybean is considered to require potassium (K) at a level 30%–50% of the N level required by the plant (Varco 1999). Over 50 years ago, some of the most striking responses of soybean to added fertilizer were by way of K salts, especially in the Southeastern United States (Ohlrogge 1960). However, many of those soils were low in available K at the onset and similar consistent increases were not obtained in the Midwest. Fertilizing with K salts is known to result in increases in pods per plant, root nodule number and total mass, improved water stress tolerance, and a decrease in disease incidence (Bharati, Wigham, and Voss 1986; Jones, Lutz, and Smith 1977). Sale and Campbell (1986) reported that a reduction in K to deficient levels for soybean plants growing in a sand culture reduced seed yields, oil levels, seed [K], and an increase in seed protein concentration. They also reported though that soybean seems to respond to K fertilization as late as anthesis. Jeffers, Schmitthenner, and Kroetz (1982) demonstrated that K nutrition and soybean seed quality were closely correlated. Soybean yields from treatments receiving added fertilizer of 372 kg K ha\(^{-1}\) were 2400 kg ha\(^{-1}\) compared to 1650 kg ha\(^{-1}\) from plots receiving no additional K. A reduction in the incidence of Phomopsis, a seed mold fungus, of 165 g kg\(^{-1}\) of seed was also noted.

Calcium is known to be vital to soybean for cell division, root hair development, as a co-factor in several enzymatic functions, and aids in plant disease resistance (Willis 1989). However, in excessive amounts it can interfere with the uptake of other cations, especially magnesium (Mg) and K. Rayar (1981) reported that maximum growth of soybean growing in nutrient solution cultures of varying [Ca] was found to occur at 249.5 µM Ca. Deficiency symptoms were noted at 24.9 µM Ca. At [Ca] > 249.5 µM Ca, tissue [P], [K], and [Mg] began to decline. Calcium is known to be immobile once taken up by the plant and is not translocated from older tissue to developing cells (Varco 1999). It is therefore essential to have an adequate supply of available Ca throughout the growing season along with sufficient water which has been shown to facilitate Ca uptake (Karlen, Hunt, and Matheny 1982).

Magnesium’s most important function in any green plant is the metal co-factor of the chlorophyll porphyrins. It is also utilized in protein construction in plants. Minimal sufficient levels of Mg in soybean have been determined to be approximately 2.6 mg g\(^{-1}\) of the dry weight. Deficiencies in Mg usually result in an interveinal chlorosis and a general unhealthy appearance of the plant. They are most frequently noticed in plants growing on light sandy soils with low cation exchange capacity (CEC’s) and seldom noticed on silts, silty clays or clay soils. As mentioned previously excesses in Ca can interfere with Mg uptake and Bruns and Abbas (2010) concluded that an excess of K fertilizer on corn (Zea mays L.) likely reduced grain yields by interfering with Mg uptake.

Sulfur is essential in the synthesis of the amino acid cysteine and methionine but has seldom been found deficient in soybean production. In a summarization of research conducted in the southeastern US Kamprath and Jones (1986) found that a response to sulfur (S) fertilizer occurred at only two of nine sites. Positive yield responses to S fertility occurred only on soils with ≤4.0 mg kg\(^{-1}\) S with no responses noted for soils with ≥8.0 mg kg\(^{-1}\) S.

Soybean production in the lower Mississippi River Valley (31° N–34° 30’ N) has undergone sweeping changes during the past 25 years. Adoption of the ESPS which involves planting MG IV
and V cultivars prior to 1 May, along with supplemental irrigation, has been fully accepted by growers in the region. Prior to development of ESPS this region grew MG V thru MG VII cultivars, planted in mid-May to early June which experienced drought and heat stress resulting in poor seed yields. Newer cultivars better adapted to the ESPS and most recently the nearly complete adoption of twin-row planting has all lent to a mean increase in yields for Mississippi alone, from approximately 1411 kg ha$^{-1}$ (Gregory and Corley 1996) to 2755 kg ha$^{-1}$ in 2011 (MSUCares.com 2014). Using the former mean yield, Varco (1999) states that the nutrient removal through seed harvest was equivalent to 123.0 kg N ha$^{-1}$, 11.2 kg P ha$^{-1}$, and 39.2 kg K ha$^{-1}$. The objectives of this experiment were (1) to acquire detailed information on some of the macro-nutrient compositions of irrigated soybean cultivars now commonly grown in the Lower Mississippi River Valley in the ESPS system and (2) to compare these data from two contrasting soils commonly used to grow soybean in the region employing recently adopted production practices to past data sets from other areas.

**Materials and methods**

The experiment was conducted during the 2011 and 2012 growing seasons at two sites. One site was a Bosket fine sandy loam site (fine-loamy, mixed, active, thermic Mollic Hapludalfs), located on the Mississippi State University Delta Branch Research and Extension Center. Soil tests prior to initiating the experiment showed this site to have a pH = 6.8, organic matter (OM) = 18.3 g kg$^{-1}$, $P = 54.0$ kg ha$^{-1}$, and $K = 53.7$ kg ha$^{-1}$. The second site was a Dundee silty clay (fine-silty, mixed, active, thermic Typic Endoaqualfs) located on private property leased by the Crop Production Systems Research Unit of the United States Department of Agriculture—Agricultural Research Service (USDA-ARS). Soil tests at this site showed a pH = 6.7, OM = 22.8 g kg$^{-1}$, $P = 38.0$ kg ha$^{-1}$, and $K = 64.9$ kg ha$^{-1}$. A pre-plant annual application of 0–33–66, N–P–K was applied both years of the experiment. The experimental design employed in the study was a randomized complete block replicated three times. Experimental units were one of three soybean cultivars, Asgrow$^1$ (Monsanto; St Louis, MO) AG4303 (MG 4.3), Pioneer$^1$ (DuPont; Johnston, IA) 94B73 (MG 4.8), and Asgrow AG5503 (MG 5.5). Plots were eight 12 m rows seeded in a twin-row configuration planted with a Monosem$^1$ NG3 (Monosem; Edwardsville, KS). Each row of a twin-row unit was spaced 25 cm apart and centered on 102 cm between units. A seeding rate of 30 seed m$^{-2}$ occurred on 14 April 2011 at both locations, 23 April 2012 on the Dundee soil, and 25 April 2012 on the Bosket soil. The previous crop at both sites in 2011 was corn (Zea mays L.) and soybean in 2012.

Weed control was achieved by the herbicide combinations of metolachloro and glyphosate applied according to label directions for soybean crops grown in Mississippi. Furrow irrigations of approximately 25.0 mm each were applied about every 10 d or 10 d after a rain event of 25.0 mm or more on the Dundee soil site beginning at growth stage V4 (four trifolates unfolded) as defined by Ritchie et al. (1994) and continuing until R7. Irrigations on the Bosket soil required a 7-d schedule due to the poor water holding capacity of the soil.

Beginning at growth stage V3 (three trifolates unfolded) and continuing at R2 (full flowering), R4 (full pod), R6 (full seed), and R8 (full maturity), three randomly selected plants from each plot were harvested from either row 2 or row 7. Sampling was done on individual cultivars as they reached the described growth stage (Ritchie et al. 1994) and as weather would permit. Leaf area of each harvested plant was measured using a LiCor$^1$ LI-3100C (Li-Cor Inc., Lincoln NE) leaf area meter at R2, R4, and R6. Leaves, stems, and pods from each plot were placed in separate bags, oven dried at 70°C for at least 76 h, weighed, and then ground to pass a 2.0 mm screen. A minimum 2.5 g sample of the ground tissue was placed a 5 ml plastic sample bottle and sealed for later analysis. Individual samples were analyzed by Waters Agricultural Laboratories, Inc.$^1$ (Camilla, GA). Total tissue [N] was determined by the LECO$^1$ combustion method as described by Sweeney and Rexroad (1987), while an open vessel wet digestion method described by Miller (1998) was used to determine all other elements analyzed in this experiment.
The four center rows of each plot were harvested at maturity (R8) for yield determination. Data for leaf area [N], [P], [K], [Ca], [Mg], and [S] along with their total contents in the leaf, stem, pod, seed, and residue (dead stem and pod tissue at harvest) were first analyzed using the PROC MIXED procedure of SAS 9.4 (Statistical Analysis System SAS Institute, Cary, NC) for individual sites combined over years with years as a fixed effect. A lack of significance between years and any interactions involving years at both sites led to the reanalysis of all data, except for leaf area and yield, with both sites and years being combined and treated as an individual random environmental effect. For these analyses, the GLIMMIX and ANOVA procedures of SAS was employed.

**Results and discussion**

Dry matter accumulation of the various plant tissues and total plant are depicted in Figure 1. Dry matter accumulation for the leaves and stems as well as the whole plant appear to have followed a sigmoidal pattern in this study as has been observed in other published data on soybean growth (Ritchie et al. 1994). The loss in total dry matter between R6 and R8 would be due to the abscission of leaflets and petioles as the plants matured. Peak leaf area occurred at R4 as shown in Figure 2. Differences in leaf area among years as shown in Figure 2 are most likely a result of slight variations in development at sampling between the 2 years. At R6 plants in 2012 had abscised more leaves by the time sampling was done than plants at this growth stage in 2011. This growth stage was reached much earlier in 2011 (mid-July) because of earlier seeding that year and a mean maximum air temperature of 36.1°C 14 d prior to sampling which likely hastened plant development (MSUCares.com 2015). In 2012 planting occurred 12 and 13 d later than 2011 and the mean maximum air temperature 14 d prior to sampling was 25.5°C which likely delayed plant development to R6 to mid-August. Total day length at this time would be approximately 30 min less than in mid-July and would stimulate leaf abscission in preparation for plant maturity, thus resulting in less leaf area per plant at R6 in 2012 than was observed in 2011 (Major et al. 1975).

The concentrations of macro-nutrients in the tissues of irrigated soybean in this experiment were observed to be similar to data reported in other studies completed well over 50 years ago (Table 1) (Ohlrogge 1960). A lack of cultivar differences or differences between soils or years does not support further research into cultivar development or soil fertility management centered on improving nutrient uptake improvement. Based on these data, improvements in soybean yields over the decades in which the crop has been a major source of farm income in the United States and elsewhere has evidently come by way of factors other than increased macro-nutrient uptake and utilization. Yield increases have likely occurred by genetic changes in plant architecture and/or pests resistance along

![Figure 1. Dry matter accumulation per plant (g) of irrigated soybean at five different growth stages and grown in twin-rows in the Lower Mississippi River Valley.](image)
with improved cultural practices such as refined planting dates, irrigation, and improved weed control. Research on increased carbon dioxide (CO\(_2\)) levels and its effect on dry bean (Phaseolus vulgaris L.) yields though have shown significant gains through CO\(_2\) fertilization (Porter and Grodzinski 1989) which would suggest that the elevated CO\(_2\) levels that has occurred over recent decades as being partly responsible for increases in seed production.

Except for Ca, micro-nutrient concentrations (Table 1) and contents (Table 2) in the leaves declined after R4. Calcium is mainly incorporated into structural tissue such as cell walls, making it immobile and much of it returns to the soil with leaf senescence. As discussed previously, leaf area peaked at R4 and then began to decline as leaves aged and started to senesces. This senescence would account for much of the decline in macro-nutrient content of Ca in the plants’ leaf tissue. However, data on macro-nutrient concentrations (Table 1) show that except for Ca, all other nutrients that were analyzed for declined between R4 and R6. These elements are mobile in plant tissue and are translocated to the strong sinks of developing seed as evidenced by the large increases in nutrient content of the pods between R4 and R6 (Table 2). This remobilization of nutrients from the leaves to developing pods and seed however does not nearly account for the large increase in nutrient content in the reproductive structures, as the concentrations of these elements in the pods either remains constant (N and S) or significantly declines (P, K, Ca, and Mg) from R4 to R6. The observed increases in content of macro-nutrients in the reproductive structures between R4 and R6 are thus a result of elements that are taken up during this time and incorporated directly into that tissue.

Macro-nutrient concentrations of stem tissue remained comparatively constant from V3 to R2 and then began to significantly decline thereafter for most elements (Table 1). By contrast, the total contents of the elements analyzed significantly increased from R2 to R6, with Ca and Mg showing significant increases between R4 and R6 (Table 2). At maturity (R8), though, the crop residue, which is largely stem tissue, showed that the contents per plant of the elements analyzed for had declined greatly from the levels observed at R6. During the sampling processes at R4 and R6, a considerable amount of the macro-nutrients contained in the stems would have been what was being translocated to the developing seed along with what was incorporated into the stem tissue itself. By R8 all translocation had ceased and only the elements incorporated into the cells of the stem would have remained.

Macro-nutrient concentrations and content of most of the elements in the seed at R8 were within range of previously published data (Bellaloui, Stetina, and Molin 2014; Morse 1950; Ohlrogge 1960; Porter and Grodzinski 1989). Except for K, Ca, and Mg, concentrations of all other elements in the seed were much higher than in the residue (Table 1). However, the total contents of all the elements in the seed were considerably greater than that remained in the residue (Table 2). Based on these data from

![Figure 2. Total plant leaf area of irrigated soybean at four growth stages grown in twin-rows at two sites in the Lower Mississippi River Valley.](image-url)
Tables 1 and 2, the 3328 kg ha\(^{-1}\) grand average seed yield (48 bu/A) of this experiment removed about 194.7 kg N ha\(^{-1}\), 16.5 kg P ha\(^{-1}\), 86.0 kg K ha\(^{-1}\), 17.5 kg Ca ha\(^{-1}\), 9.0 kg Mg ha\(^{-1}\), and 10.4 kg S ha\(^{-1}\). The amount of macro-nutrients returned to the soil in the residue and abscised leaves were not calculated in this experiment because the total weight of that material per hectare was not determined. It would not be possible in the field to determine from what plant abscised leaves between R4 and R6 had come from and by R8 those leaves would be badly decomposed. The amount of the measured elements available from this soybean residue for succeeding crops will be very dependent on fall and winter rainfall, temperature, and soil type that influence leaching, microbial activity, as well as the pH of the soil.

The macro-nutrient contents of the whole plant at the observed growth stages are presented in Table 3. Two elements (N and P) had significant \((P \leq 0.05)\) steady increases in content from R2 to R8, while S content significantly increased from R2 to R6 and tended towards an increase from R6 to R8. Nutritionally soybean is known to be a rich source of protein for human and livestock diets but a comparatively high producer of phythate, a P storage compound in plants that is important in germination but indigestible by humans and monogastric animals. This can lead to deficiencies in iron (Fe) and zinc (Zn) by binding with phythate in the gut, preventing these elements from being absorbed into body (Andrews 2015).

Sulfur is a component of the essential amino acids cysteine and methionine which are incorporated into the protein contained in the seed. These factors help explain the continued increase in N, P, and S throughout the growing season. Potassium, Ca, and Mg are not as much of a seed component and appear primarily in structural tissue (Ca), water utilization and enzymatic reactions (K), particularly photosynthesis (K and Mg) and the overall seasonal growth of the plant.
Data on the cultivars used in this experiment showed no consistent differences in nutrient concentration or content during the growing season (Table 4). At maturity (R8) there were significant ($P \leq 0.05$) differences in residue dry weight between all three cultivars along with total P content (Table 4). Other differences were noted between AG5503 and the other two cultivars for total N, and K content and between AG4403 and the other two cultivars for total Ca and Mg content. No significant differences were noted among the three cultivars for total S content in the residue. No significant differences between cultivars were observed for seed weight per plant or total macro-nutrient content of any of the elements analyzed (Table 4).
Conclusion

Based on these data, it appears that macro-nutrient concentrations in soybean has basically remained unchanged despite improvements in yield. These data do not encourage the exploration of improving soybean yields by seeking changes in nutrient uptake and utilization by the plant. It does provide information on nutrient concentration and content of soybean which has largely been ignored for nearly 50 y. Data such as this can be useful in revising and refining soil fertility recommendations for soybean production which could be useful given the steady increase in seed yields (41.6 kg ha\(^{-1}\) y\(^{-1}\)) over the past 25 y (USDA-NASS 2015).

Disclaimer

Trade names used in this publication are solely for the purpose of providing specific information. Mention of a trade name, propriety product, or specific equipment does not constitute a guarantee or warranty by the USDA-ARS and does not imply approval of the named product to exclusion of other similar products. The author declares there is no conflict of interests regarding the publication of this article.

References


Table 4. Total plant nutrient content (mg) in the crop residue and seed of three irrigated soybean cultivars at maturity (R8) over two growing seasons grown at two sites in the lower Mississippi River Valley\(^{1}\).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Residue wt (g)</th>
<th>Total N</th>
<th>Total P</th>
<th>Total K</th>
<th>Total Ca</th>
<th>Total Mg</th>
<th>Total S</th>
</tr>
</thead>
<tbody>
<tr>
<td>94B73</td>
<td>9.01</td>
<td>99.72</td>
<td>10.45</td>
<td>164.84</td>
<td>99.87</td>
<td>40.2</td>
<td>8.97</td>
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<td>AG4303</td>
<td>6.29</td>
<td>66.08</td>
<td>8.55</td>
<td>158.73</td>
<td>61.87</td>
<td>30.34</td>
<td>5.62</td>
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<tr>
<td>AG5503</td>
<td>12.41</td>
<td>141.65</td>
<td>19.5</td>
<td>245.74</td>
<td>99.74</td>
<td>44.49</td>
<td>10.98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Seed wt (g)</th>
<th>Total N mg</th>
<th>Total P mg</th>
<th>Total K</th>
<th>Total Ca</th>
<th>Total Mg</th>
<th>Total S</th>
</tr>
</thead>
<tbody>
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<td>94B73</td>
<td>23.3</td>
<td>1373.11</td>
<td>132.3</td>
<td>500.48</td>
<td>117.76</td>
<td>62.78</td>
<td>75.72</td>
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<td>22.1</td>
<td>1275.27</td>
<td>127.47</td>
<td>473.13</td>
<td>120.74</td>
<td>65.2</td>
<td>73.84</td>
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<td>AG5503</td>
<td>24.6</td>
<td>288.61</td>
<td>130.01</td>
<td>541.37</td>
<td>134.17</td>
<td>63.09</td>
<td>73.62</td>
</tr>
</tbody>
</table>

\(^{1}\)Means of two sites, 2 years (2011 and 2012), three replications, and three plants. Means within a column that are bolded are significantly different @ P ≤ 0.05 from other means within the same column of data.


