Reprinted from *Agronomy Journal*
Vol. 74, March-April 1982, p. 347-354

# Accumulation and Distribution of K, Ca, and Mg by Selected Determinate Soybean Cultivars Grown With and Without Irrigation[1]

**D. L. Karlen, P. G. Hunt, and T. A. Matheny**[2]

## ABSTRACT

**Reports on nutrient accumulation and distribution by determinate soybeans [*Glycine max*. (L.) Merr.] when grown under field conditions have seldom compared irrigated and nonirrigated management or attempted to measure differences among cultivars. To provide this information we grew three or four determinate soybean cultivars from Maturity Group VI, VII, or VIII with or without irrigation on a Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Paleudults) during 1978 and 1979. Plant samples were collected periodically throughout the growing season to measure dry matter accumulation and distribution among the leaves. petioles, stems, and pods. Plant fractions were analyzed for K, Ca, and Mg to measure nutrient accumulation and distribution. The two growing seasons during which the soybeans were grown had distinctly different rainfall patterns. In 1978 a drought existed for most of the reproductive growth period, while in 1979 a drought occurred during the vegetative growth stages. Also, in 1979 the soil water content below 30 cm was generally higher throughout the entire growing season. Potassium, Ca, and Mg concentrations and accumulations were all greater during 1979, but even with irrigation, yields averaged only 1.95 metric tons/ha compared to irrigated yields of 3.16 metric tons/ha in 1978. Nonirrigated yields averaged 1.72 and 1.62 metric tons/ha in 1978 and 1979. The lower yields in 1979 may have been caused by very wet soils following Hurricane David which may have reduced $O_2$ levels during pod fill. The uptake patterns of K, Ca, and Mg showed different responses to water stress, probably because of differences in the mechanism by which these nutrients move to plant roots. Potassium uptake under nonirrigated (stressed) conditions fluctuated with water availability, whereas K uptake under nonstressed (irrigated) conditions was relatively constant until physiological maturity. Calcium and Mg uptake were relatively constant regardless of stress until physiological maturity. Differences in nutrient concentrations and accumulations among cultivars were generally not statistically significant, although the Ransom cultivar frequently had the highest nutrient concentrations and also produced the highest seed yield. Irrigation did not significantly change the cation concentrations within the soybean plant. Therefore, differences in cation accumulation were primarily caused by increased plant growth.**

***Additional index words:*** **Soybean cultivars, Soil water management, Nutrient accumulation, *Glycine max* L. Merr.**

IRRIGATION of soybeans [*Glycine max* (L.) Merr.] throughout the Southeast is increasing to prevent yield reductions caused by erratic rainfall and soils which have low water-holding capacities. However, few field experiments designed to study nutrient accumulation and distribution in determinate soybeans have included irrigated and nonirrigated growing conditions. Terman (1977) applied small quantities of irrigation water when needed in his field experiments, but only Bachelor and Scott (1979) have reported specific nutrient accumulation responses by irrigated and nonirrigated determinate soybeans grown under field conditions.

Viets (1967), in reviewing the relationships between nutrient availability and soil water status, discussed diffusion along concentration gradients, mass flow relationships, the nutrient-concentrating effect of decreasing soil water content, and changes in the soil solution if oxygen becomes limited. Oliver and Barber (1966) showed that diffusion was the primary mechanism for transport of K, while Ca and Mg moved to soybean roots primarily through mass flow. Utilizing the principles of thermodynamics, Marshall (1977) summarized the dynamic nature of monovalent-divalent cation equilibria in relation to moisture cycles. To maintain a constant cation activity ratio in the soil solution as soils dry, there must be a change in the proportion of the cations in the solution. These changes can be assumed to influence the transport mechanisms and thus be reflected in the cation composition of the plant tissue. Karlen et al. (1980) demonstrated these relationships by showing that changes in accumulations of K, Ca, and Mg by wheat (*Triticum aestivum*) plants were similar to changes in the nutrient concentrations in the soil solution as the soil water content varied.

The effects of genetic variation in relation to nutrient accumulation by soybeans were reviewed by DeMooy et al. (1973). Raper and Barber (1970) showed that differences in K absorption potential by soybeans could be related to root morphology. Several indeterminate soybean cultivars have been studied in field experiments to evaluate nutrient accumulation and distribution (Hammond et al., 1951; Hanway and Weber, 1971), but the only determinate cultivar studied under field conditions was Lee (Henderson and Kamprath, 1970; Terman, 1977; and Bachelor and Scott, 1979).

In their review, DeMooy et al. (1973) reported that varying weather conditions influenced soybean growth,

---

[1] Contribution of the Coastal Plains Soil and Water Conservation Research Center, USDA-ARS, Florence, SC 29502 in cooperation with the S. C. Agric. Exp. Stn. Presented in part before Div. S-4, Soil Sci. Soc. of Am., Dec. 1980. Received 11 May 1981.

[2] Soil scientists, Florence, SC 29502.

**Table 1. Chemical properties of a Norfolk loamy sand where experiments to measure K, Ca, and Mg accumulations by determinate soybeans were conducted.**

| Horizon | Year | Water pH | K | Ca | Mg | P | Zn | Mn | Fe |
|---|---|---|---|---|---|---|---|---|---|
| | | | ppm | | | | | | |
| $A_p$ | 1978 | 6.1 | 55 | 194 | 81 | 65 | 1.7 | 13 | 46 |
| $A_p$ | 1979 | 5.6 | 70 | 194 | 87 | 61 | 1.5 | 14 | 40 |
| B | 1978 | 5.0 | 94 | 190 | 114 | 4 | 0.4 | 2 | 28 |
| B | 1979 | 4.7 | 66 | 236 | 89 | 2 | 0.6 | 2 | 13 |

(K through Fe: Dilute double acid extractable)

**Table 2. Distribution and amount of rainfall and irrigation received by soybeans during 1978 and 1979.**

| Days after planting | Rainfall 1978 | Rainfall 1979 | Irrigation 1978 | Irrigation 1979 |
|---|---|---|---|---|
| | mm | | | |
| 7 | 0 | 30 | 0 | 0 |
| 14 | 51 | 3 | 0 | 0 |
| 21 | 43 | 1 | 0 | 20 |
| 28 | 20 | 76 | 0 | 0 |
| 35 | 71 | 7 | 0 | 0 |
| 42 | 32 | 0 | 0 | 11 |
| 49 | 37 | 14 | 0 | 28 |
| 56 | 16 | 62 | 0 | 25 |
| 63 | 23 | 44 | 0 | 0 |
| 70 | 28 | 0 | 0 | 0 |
| 77 | 2 | 0 | 68 | 57 |
| 84 | 10 | 7 | 50 | 32 |
| 91 | 41 | 33 | 13 | 53 |
| 98 | 11 | 12 | 21 | 19 |
| 105 | 0 | 205 | 22 | 0 |
| 112 | 11 | 7 | 22 | 0 |
| 119 | 1 | 4 | 6 | 0 |
| 126 | 0 | 18 | 0 | 0 |
| 133 | 0 | 72 | 0 | 0 |
| 140 | 0 | 10 | 0 | 0 |
| 147 | 2 | 1 | 0 | 0 |
| 154 | 4 | 19 | 0 | 0 |

**Table 3. Yields of selected determinate soybean cultivars grown with and without irrigation in experiments where K, Ca, and Mg accumulation and distribution were measured.**

| Cultivar | 1978 Irrigated | 1978 Nonirrigated | 1979 Irrigated | 1979 Nonirrigated |
|---|---|---|---|---|
| | metric ton/ha (13% moisture) | | | |
| Bragg | 2.89 b† | 1.55 d | 1.96 a | 1.67 a |
| Coker 338 | 3.07 b | 1.59 d | 1.73 a | 1.44 a |
| Lee | -- | -- | 1.80 a | 1.65 a |
| Ransom | 3.52 a | 2.02 c | 2.32 b | 1.74 a |

† Values within a year followed by the same letter are not significantly different at P (0.05).

nutrient accumulation, and yield. Periods of drought allowed plant roots to deplete the soil water until further growth and nutrient absorption were inhibited. Nutrient accumulation was affected in proportion to the number of days of effective drought during the season and to the portion of the root system located in the water-depleted soil.

The purpose of this research was to investigate the influence of water management, cultivar, and seasonal weather pattern on K, Ca, and Mg accumulations, distribution, and seed yield of selected soybean cultivars grown on a Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Paleudults) in 1978 and 1979.

## METHODS AND MATERIALS

The experimental designs were a split plot in 1978 and a randomized complete block in 1979. The plot size was 5.8 × 10.7 m. Each treatment was replicated three times. The nutrient status of the soil (Table 1) was determined by using a dilute double acid extract (0.05 *N* HCl in 0.025 *N* $H_2SO_4$) (Isaac, 1977). Analyses of the Ap horizon indicated medium K, low Ca, high Mg, very high P, and adequate micronutrient concentrations. Fertilizer applications included 220 kg/ha 0-14-22 in 1978 and 202 kg/ha 0-20-20 in 1979. Treflan[3] (trifluralin) was applied at 0.3 l/ha before planting and incorporated by disking.

Three cultivars ('Ransom,' 'Bragg,' and 'Coker 338') were planted in 0.96 m (38") rows on 12 June 1978, and four cultivars ('Lee,' Ransom, Bragg, and Coker 338) were planted in 0.96 m (38") rows on 24 May 1979. The cultivars were selected to represent Maturity Groups VI, VII, and VIII. Stand counts taken approximately 2 weeks after emergence showed plant densities of 26 plants/m$^2$ in 1978 and 20 plants/m$^2$ in 1979. The lower plant density in 1979 was caused by planter malfunction. Supplemental irrigation was applied during the pod fill growth stage in 1978, and during the late vegetative and flowering growth stages in 1979. Irrigation amounts (Table 2) were determined by estimating evapotranspiration at 6 mm/day and applying supplemental water to meet this demand. Soil water tensions were monitored with vacuum gauge tensiometers placed at 30-, 60-, 90-, 120-, and 150-cm depths. On-site weather data were collected continuously starting in August 1978.

Whole plant samples were collected from approximately 30 cm of row during vegetative, flowering (R2), early (R4), and late (R6) pod development. Plants were partitioned into leaves, stems, petioles, and pods; rinsed in demineralized water; dried at 70 C; ground to pass a 0.84 mm sieve in 1978 or a 0.50 mm screen in 1979; and digested with a 1:1 mixture of nitric and perchloric acids. The K concentration was determined by flame emission while Ca and Mg concentrations were determined by atomic absorption. A solution of 1% La was added to prevent anion interference in Ca analysis. Soybean yields were measured by collecting the four center rows, drying them at 50 C, and threshing. Seed yields were calculated at 13% moisture. Data were analyzed using least significant difference (L.S.D.) and Duncan's Multiple Range Test at P(0.05) as outlined by Steel and Torrie (1960).

## RESULTS AND DISCUSSION

The rainfall distribution associated with the 1978 and 1979 soybean growing seasons was different (Table 2). In 1978 there was a prolonged drought throughout the pod-filling period, while during 1979 two short-term droughts occurred during the vegetative and flowering growth stages. However, during pod fill in 1979 extremely wet conditions were caused by excessive rainfall associated with Hurricane David. These distinctly different weather patterns illustrate the erratic rainfall which can occur throughout the southeastern United States, thus influencing annual soybean production through both water deficiences and excesses.

The varietal by irrigation interaction in these experiments was generally statistically nonsignificant for all measurements, but when the interaction was sig-

---

[3] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Dep. of Agric. or the S.C. Agric. Exp. Stn. and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

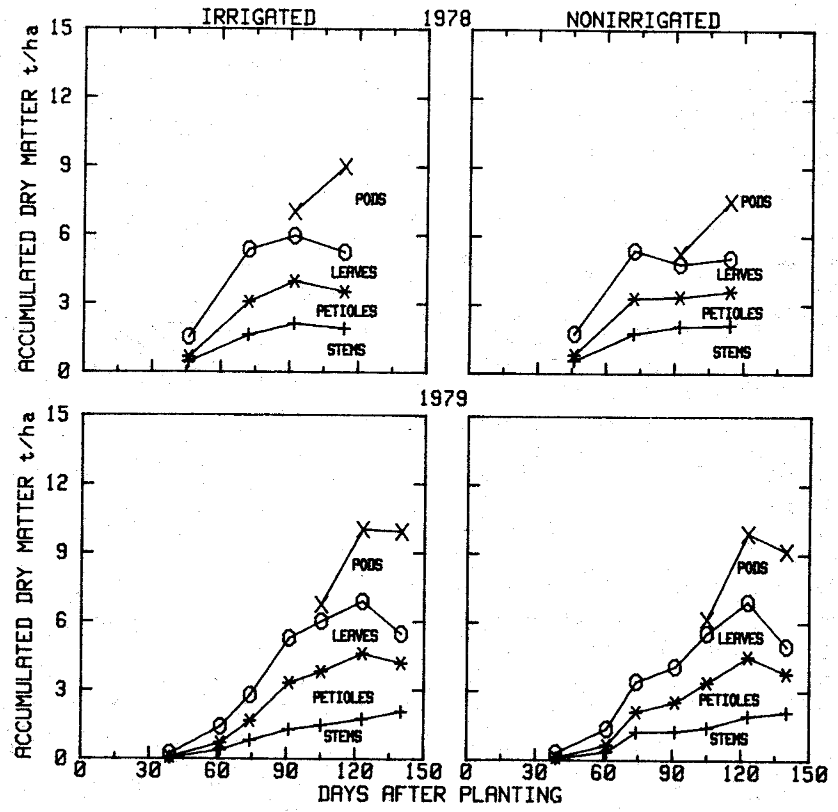

**Fig. 1.** Accumulation and distribution of dry matter by soybeans grown with and without irrigation. Note: The figures are cumulative over time, but do not include plant fractions which had fallen from the stem. The actual amount within any plant fraction can be obtained by subtraction of any two points.

nificant, the F values were quite low and there were no consistent trends. Therefore, irrigation and varietal responses will be discussed separately as main effects.

## Plant Growth

The average accumulation and distribution of dry matter for three cultivars in 1979 and four cultivars in 1980 are shown in Fig. 1. In 1978, without irrigation, there was a plateau in total dry matter accumulation between samples collected 72 and 92 days after planting. This was during a period of severe drought (Table 2) and was caused by a loss of leaves, petioles, and a slower rate of pod development by the nonirrigated plants. In 1979 periods of drought occurred earlier in the season and the only significant response to supplemental irrigation was for the samples collected 90 days after planting. This irrigation response was due to a greater dry matter accumulation in the leaf and petiole fractions, because pod development was insignificant at this time. Excessive rainfall associated with Hurricane David eliminated the need for supplemental irrigation during pod fill in 1979. This caused the total above-ground dry matter production for both irrigated and nonirrigated treatments to be essentially the same by the end of the growing season.

The relationship between total aboveground dry matter production and soybean seed yield (Table 3) was different for the 2 years. DeMooy et al. (1973) cited work by Neunylov and Slabko (1968) which showed that temperature and humidity variations between individual seasons had a strong effect on soybean plants and may override the effects of nutrients. Neunylov and Slabko (1968) calculated average seed/total aboveground plant weight ratios and reported values of approximately 0.35 in good seasons and 0.21 in poor seasons. Calculating similar ratios, for our data in 1978, shows that with supplemental irrigation, the three cultivars have an average ratio of 0.35 with a range of 0.34 to 0.36, while without the supplemental irrigation, the ratio averaged 0.23 with a range of 0.19 to 0.29. In 1979 the ratios with and without supplemental irrigation averaged 0.17 and 0.16, respectively, with ranges of 0.14 to 0.19 and 0.14 to 0.17.

The validity and usefulness of calculating such ratios may be subject to debate, but in 1978 when supplemental irrigation was applied to relieve the environmental stress, our ratios were similar to those reported for good seasons. Without supplemental irrigation to meet the estimated evapotranspiration, our ratios were similar to those reported for poor seasons. Our ratios for 1979, with or without supplemental irrigation, are lower than any reported by Neunylov and Slabko (1968). This was apparently caused by high aboveground plant dry matter production, but relatively low seed yields. The reasons for this are not known although Campbell and Phene (1977) showed that excessive rainfall on similar Coastal Plain soils can depress soil $O_2$ levels and reduce yields. The amount of rainfall received during pod fill may have severely reduced the seed yields regardless of cultivar or previous irrigation treatment and thus resulted in the very low seed to aboveground plant dry matter ratios. Finally, our work agrees with work by Doss

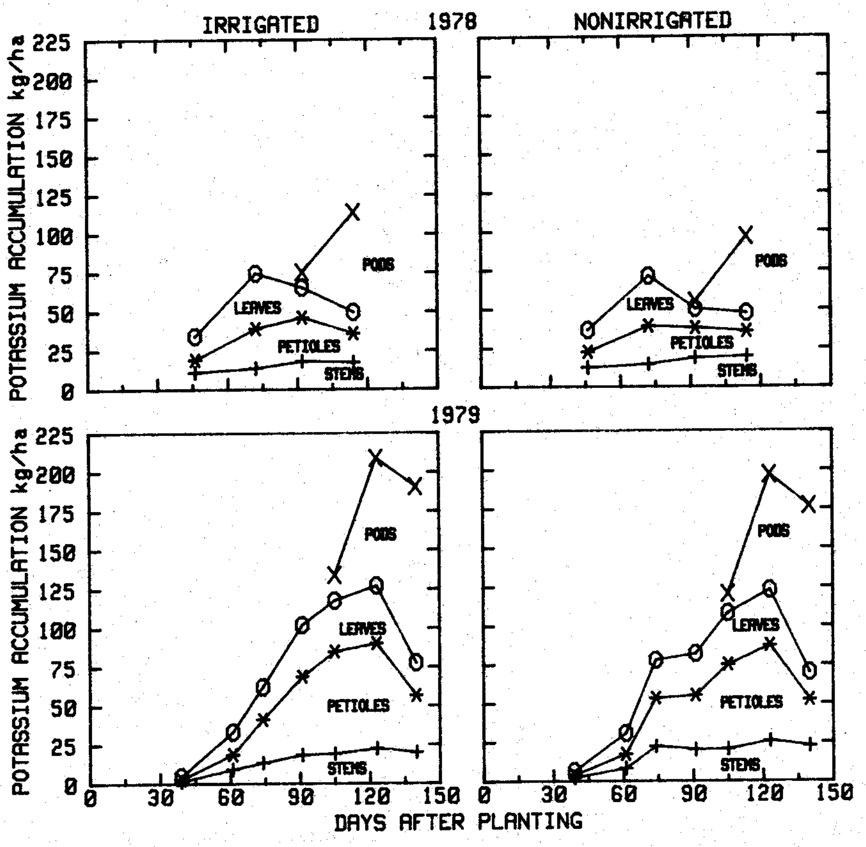

Fig. 2. Accumulation and distribution of K by soybeans grown with and without irrigation. See Note, Fig. 1.

et al. (1974) and others that water stress during pod fill is most critical with respect to soybean seed yield.

## Potassium

Average K accumulation and distribution within the soybean cultivars grown with and without supplemental irrigation are shown in Fig. 2. The maximum amounts of K accumulated with and without irrigation were 133 and 97 kg/ha in 1978 and 209 and 197 kg/ha in 1979. The irrigation response was significant only at the sampling 114 days after planting in 1978. This was primarily the result of greater pod development because K concentrations in individual plant fractions were generally not significantly influenced by supplemental irrigation in either year (Table 4). The higher total K accumulation in 1979 reflected slightly greater dry matter production and higher K concentrations in all plant fractions (Table 4). The higher K concentrations in 1979 were probably the result of lower soil water tensions in the B horizon (unpublished data). Applying supplemental irrigation in 1978 to meet an estimated evapotranspiration of 6 mm/day was sufficient to maintain plant growth and to produce a significant yield response, but it did not significantly influence the soil water content below 30 cm (unpublished data). Oliver and Barber (1966) showed that K moved to soybean roots primarily by diffusion. These Coastal Plain soils retain a large amount of the K in the B horizon below 45 cm; therefore, the K uptake rate in 1978 was probably reduced by slower diffusion rates. Figure 2 supports this hypothesis because in 1978 without irrigation, K accumulation in the leaf fraction declined very rapidly during the period 72 to 92 days after planting. In 1979 the short-term drought caused a depletion of the soil water to a depth of 120 cm which also reduced K accumulation during the period 74 to 91 days after planting. These results indicate that even short-term drought will reduce K uptake by plants growing in these soils, presumably by reducing the K diffusion rates.

An essential assumption in the nutrient translocation model developed by Scott and Brewer (1980) was that during vegetative or reproductive growth stages, the nutrient uptake rate must be constant. Our 1979 K data agree with this assumption where irrigation water was applied, but the other data do not, primarily because K accumulation during periods of water stress was not linear with time. This indicates that to apply their model, stress must be absent or uniform throughout the growth period being studied.

The effects of supplemental irrigation on the K concentration in various fractions of the soybean plant at selected growth stages are summarized in Table 4. There were no significant differences in the K concentration in any of the plant fractions in 1978. In 1979 differences in the leaf and stem fraction were slight, while petiole and pod K concentrations were not influenced by supplemental irrigation. Potassium concentrations in leaves, petioles, and stems generally decreased throughout the growing season, while K concentrations in the pod fraction increased during seed formation. Higher K concentrations in the leaf,

**Table 4. Effects of irrigation on K, Ca, and Mg concentrations in determinate soybeans at selected growth stages.†**

| Year — water management | K |  |  |  | Ca |  |  |  | Mg |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Leaf | Petiole | Stem | Pod | Leaf | Petiole | Stem | Pod | Leaf | Petiole | Stem | Pod |
|  | % |  |  |  |  |  |  |  |  |  |  |  |
| 45 days after planting (V12)§ |  |  |  |  |  |  |  |  |  |  |  |  |
| 1978 |  |  |  |  |  |  |  |  |  |  |  |  |
| Irrigated | 1.73 a‡ | 3.91 a | 2.39 a | – | 0.75 a | 0.90 a | 0.53 a | – | 0.50 a | 0.49 a | 0.40 a | – |
| Nonirrigated | 1.55 a | 4.09 a | 2.19 a | – | 0.77 a | 0.96 b | 0.54 a | – | 0.51 a | 0.54 a | 0.42 a | – |
| 72 days after planting (R3) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1978 |  |  |  |  |  |  |  |  |  |  |  |  |
| Irrigated | 1.52 a | 1.73 a | 0.82 a | – | 0.88 a | 0.69 a | 0.40 a | – | 0.52 a | 0.40 a | 0.41 a | – |
| Nonirrigated | 1.51 a | 1.46 a | 0.81 a | – | 0.88 a | 0.72 a | 0.43 b | – | 0.53 a | 0.43 a | 0.44 a | – |
| 114 days after planting (R6) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1978 |  |  |  |  |  |  |  |  |  |  |  |  |
| Irrigated | 0.80 a | 1.15 a | 0.90 a | 2.20 a | 1.25 a | 0.77 a | 0.31 a | 0.47 a | 0.39 a | 0.46 a | 0.36 a | 0.45 a |
| Nonirrigated | 0.82 a | 1.09 a | 0.96 a | 2.00 a | 1.13 a | 0.72 a | 0.33 a | 0.45 a | 0.44 a | 0.45 a | 0.39 a | 0.40 a |
| 38 days after planting (V10) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1979 |  |  |  |  |  |  |  |  |  |  |  |  |
| Irrigated | 1.37 a | 4.88 a | 2.61 a | – | 1.06 a | 1.36 a | 0.90 a | – | 0.69 a | 0.66 a | 0.57 a | – |
| Nonirrigated | 1.34 a | 5.10 a | 2.73 a | – | 1.14 b | 1.46 b | 0.89 a | – | 0.65 a | 0.62 a | 0.55 a | – |
| 90 days after planting (R3) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1979 |  |  |  |  |  |  |  |  |  |  |  |  |
| Irrigated | 1.69 a | 2.44 a | 1.41 a | – | 1.04 a | 0.85 a | 0.42 a | – | 0.55 a | 0.52 a | 0.44 a | – |
| Nonirrigated | 1.75 a | 2.61 a | 1.57 b | – | 1.08 a | 0.93 b | 0.42 a | – | 0.54 a | 0.50 a | 0.42 a | – |
| 122 days after planting (R6) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1979 |  |  |  |  |  |  |  |  |  |  |  |  |
| Irrigated | 1.64 b | 2.48 a | 1.30 a | 2.60 a | 1.37 a | 0.89 a | 0.45 a | 0.66 a | 0.55 a | 0.54 a | 0.40 a | 0.60 a |
| Nonirrigated | 1.50 a | 2.40 a | 1.34 a | 2.47 a | 1.38 a | 0.88 a | 0.41 a | 0.58 a | 0.51 a | 0.55 a | 0.36 a | 0.58 a |

† Average values across three replicates and three or four cultivars.

‡ Values within a plant fraction and sampling date followed by the same letter are not significantly different at P (0.05).

§ Growth stage, Fehr et al. (1971).

**Table 5. Concentrations of K, Ca, and Mg in determinate soybean cultivars sampled at selected growth stages.†**

| Year — cultivar | K |  |  |  | Ca |  |  |  | Mg |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Leaf | Petiole | Stem | Pod | Leaf | Petiole | Stem | Pod | Leaf | Petiole | Stem | Pod |
| 45 days after planting (V12)§ |  |  |  |  |  |  |  |  |  |  |  |  |
| 1978 |  |  |  |  |  |  |  |  |  |  |  |  |
| Bragg | 1.58 a‡ | 4.14 a | 2.23 a | – | 0.80 a | 0.98 a | 0.58 b | – | 0.50 a | 0.52 a | 0.40 ab | – |
| Coker 338 | 1.51 a | 3.95 a | 2.13 a | – | 0.78 a | 0.94 a | 0.55 b | – | 0.51 a | 0.46 a | 0.37 a | – |
| Ransom | 1.84 a | 3.91 a | 2.50 a | – | 0.70 a | 0.87 a | 0.48 a | – | 0.51 a | 0.56 a | 0.46 b | – |
| 92 days after planting (R5) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1978 |  |  |  |  |  |  |  |  |  |  |  |  |
| Bragg | 0.86 a | 1.76 a | 0.85 a | 1.11 a | 1.03 a | 0.62 a | 0.38 a | 0.76 a | 0.48 a | 0.37 a | 0.38 a | 0.50 a |
| Coker 338 | 0.96 a | 1.29 a | 0.76 a | 0.91 a | 0.96 a | 0.74 b | 0.40 a | 1.00 b | 0.43 a | 0.36 a | 0.44 b | 0.50 a |
| Ransom | 0.94 a | 1.62 a | 1.06 a | 0.87 a | 0.91 a | 0.68 ab | 0.34 a | 0.69 a | 0.49 a | 0.44 a | 0.50 c | 0.51 a |
| 38 days after planting (V10) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1979 |  |  |  |  |  |  |  |  |  |  |  |  |
| Bragg | 1.28 a | 5.23 a | 2.30 a | – | 1.16 b | 1.40 b | 0.89 a | – | 0.71 a | 0.68 a | 0.59 b | – |
| Coker 338 | 1.47 a | 4.73 a | 2.69 a | – | 1.19 b | 1.63 c | 0.97 b | – | 0.70 a | 0.68 a | 0.60 b | – |
| Lee | 1.34 a | 4.89 a | 3.00 a | – | 0.94 a | 1.26 a | 0.89 a | – | 0.63 a | 0.60 a | 0.53 a | – |
| Ransom | 1.33 a | 5.11 a | 2.69 a | – | 1.10 b | 1.36 b | 0.84 a | – | 0.63 a | 0.59 a | 0.51 a | – |
| 122 days after planting (R5) |  |  |  |  |  |  |  |  |  |  |  |  |
| 1979 |  |  |  |  |  |  |  |  |  |  |  |  |
| Bragg | 1.51 a | 2.40 b | 1.27 a | 2.65 a | 1.44 b | 0.89 a | 0.43 a | 0.66 a | 0.58 a | 0.57 a | 0.40 a | 0.63 a |
| Coker 338 | 1.48 a | 1.95 a | 1.20 a | 2.52 a | 1.32 a | 0.85 a | 0.42 a | 0.60 a | 0.55 a | 0.53 a | 0.35 a | 0.58 a |
| Lee | 1.58 a | 2.59 bc | 1.31 a | 2.55 a | 1.45 b | 0.87 a | 0.47 a | 0.69 a | 0.55 a | 0.56 a | 0.40 a | 0.64 a |
| Ransom | 1.69 a | 2.82 c | 1.50 b | 2.42 a | 1.28 a | 0.93 a | 0.41 a | 0.54 a | 0.44 a | 0.52 a | 0.36 a | 0.52 a |

† Average values for three replicates with and without supplemental irrigation.

‡ Values within a plant fraction and sampling date followed by the same letter are not significantly different at P (0.05).

§ Growth stage, Fehr et al. (1971).

petiole, and stem fractions during the early vegetative growth stages support the observation by Henderson and Kamprath (1970) that K accumulation was relatively more rapid than dry matter accumulation during the early growth stages, but the period of maximum K accumulation within the plant was during the reproductive growth stages.

The distribution of K among the plant fractions is also shown in Fig. 2. Accumulations in the leaf and petiole fractions increased until the latter reproductive stages when there was a rapid translocation into the pods and a concurrent loss of K from the leaves and petioles. The K content within the stem fraction increased during the early vegetative growth stages, but remained relatively constant throughout pod fill. Potassium accumulation in the pods increased rapidly during seed formation with approximately 62 and 72% of the total K being taken up after beginning bloom

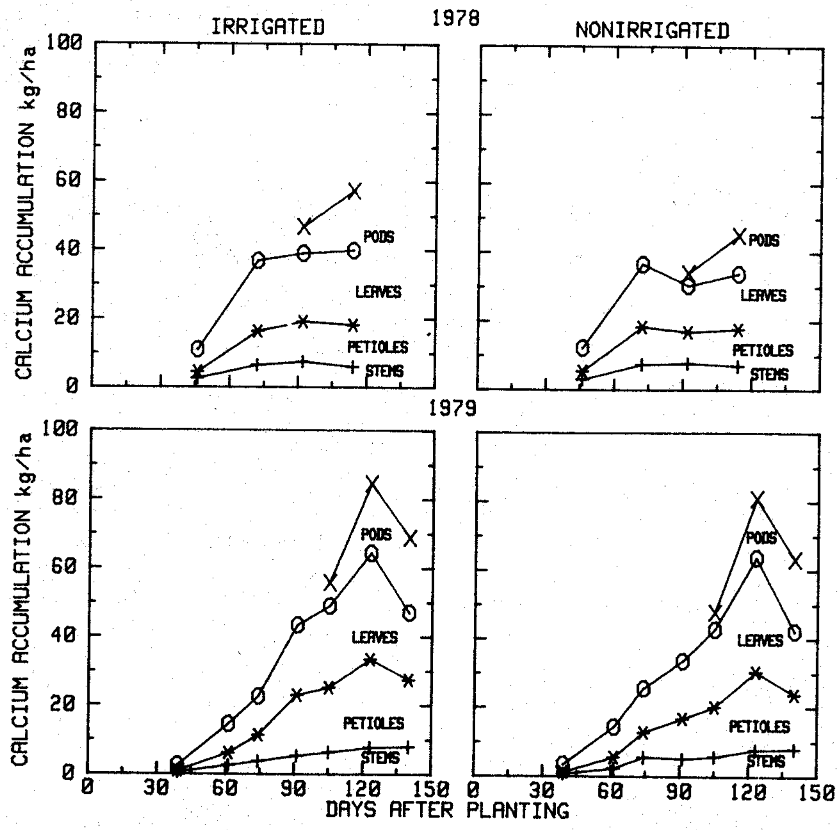

Fig. 3. Accumulation and distribution of Ca by soybeans grown with and without irrigation. See Note, Fig. 1.

by the nonirrigated and irrigated soybeans. This agrees with the report by Bachelor and Scott (1979) that 65% of the total K accumulated by irrigated soybeans was absorbed after flowering began.

Varietal differences in K concentrations within the various plant fractions at selected growth stages are summarized in Table 5. The differences in K concentration among the varieties were generally nonsignificant, but when significant, the cv. Ransom had the highest K concentration. Varietal differences in total K accumulation were also generally nonsignificant. In all samplings the K concentration was within the normal ranges reported by DeMooy et al. (1973) and Small and Ohlrogge (1973).

## Calcium

The average accumulation and distribution of Ca by soybean plants grown with and without irrigation are shown in Fig. 3. Maximum accumulation with and without irrigation averaged 57 and 45 kg/ha in 1978 and 85 and 81 kg/ha in 1979. Total Ca accumulation increased steadily until late pod fill when leaf and petiole abscission caused the measured Ca accumulation to decline. Henderson and Kamprath (1970) reported that Ca accumulation peaked at about 110 to 120 days after planting, which coincides with data reported here. Irrigation increased total Ca accumulation primarily by increasing leaf and petiole growth during periods of drought and severe water stress. Differences in total Ca accumulation among cultivars were generally nonsignificant.

We also utilized our Ca data to test Scott and Brewer's (1980) hypothesis of constant nutrient uptake throughout either vegetative or reproductive growth stages. Unlike the K data which fit only under irrigated conditions in 1979, our Ca data agreed with their hypothesis except for the nonirrigated treatments in 1978. The difference in response was probably because Ca moves to plant roots primarily by mass flow rather than diffusion. In 1978 the nonirrigated plots suffered severe drought stress which limited growth and thus nutrient accumulation during the period 72 to 92 days after planting.

The effects of supplemental irrigation on Ca concentrations in the various plant fractions are presented in Table 4. The primary effect of irrigation on Ca concentration was a slight depression during the early growth stages. This was primarily dilution caused by more rapid growth of the irrigated plants. Irrigation had no effect on the Ca concentration in any plant fraction during the latter reproductive growth stages.

The Ca concentrations in the various plant fractions of each cultivar at selected sampling dates are summarized in Table 5. Although differences among cultivars occurred in all plant fractions, there was no consistent pattern. The Ca concentrations in all samples were within the normal ranges reported by DeMooy et al. (1973) and Small and Ohlrogge (1973). Calcium concentrations in the leaf and petiole fractions declined during the early reproductive stages, but increased as the plant matured. The Ca concentration in the stem fraction declined rapidly as dry matter production increased early in the growing season, but it remained relatively constant at approximately 0.4% throughout pod fill.

The distribution of Ca among plant fractions throughout the growing season is shown in Fig. 3. In

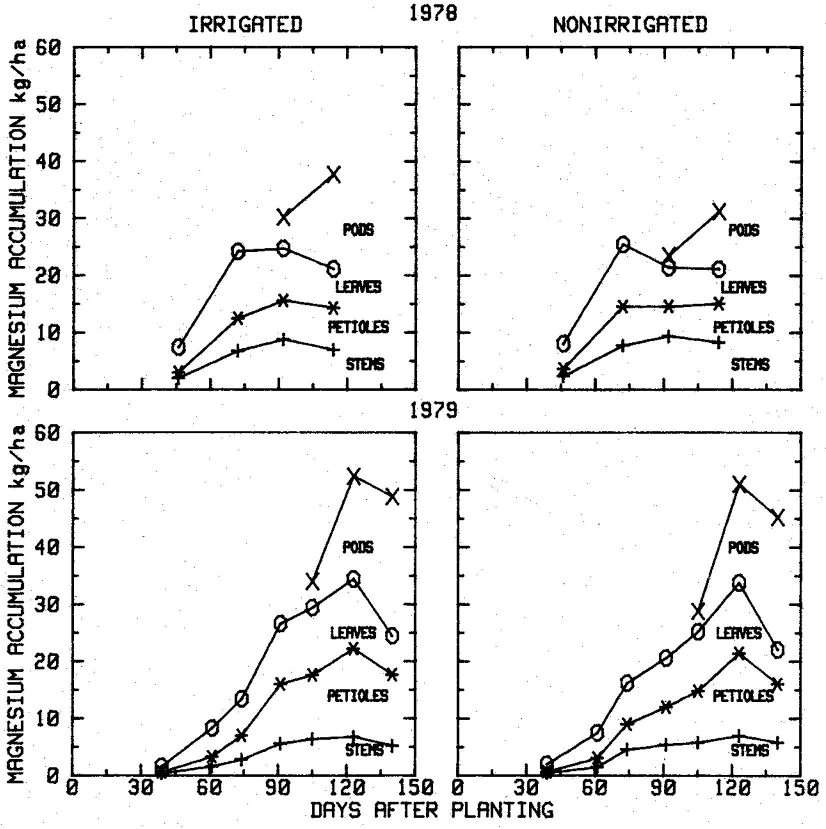

**Fig. 4. Accumulation and distribution of Mg by soybeans grown with and without irrigation. See Note, Fig. 1.**

1979, the rapid decline in Ca accumulation in the leaf and petiole fraction near maturity was attributed to leaf drop and petiole abscission. Fallen plant fractions were not collected to verify this, but there were no major changes in the amount of Ca in the stem or pod fraction between samplings taken 123 and 140 days after planting. The inverse relationship between Ca concentration and accumulation in the pod fraction during seed development indicates that there was very little translocation of Ca from the vegetative fractions to the developing seeds. Our results substantiate earlier conclusions that the supply of soil Ca during the late growth stages would not be as critical for soybeans as the Ca supply during early growth.

## Magnesium

The average accumulation and distribution of Mg by soybean plants grown with and without irrigation are shown in Fig. 4. Maximum accumulation with and without irrigation averaged 39 and 32 kg/ha in 1978 and 52 and 51 kg/ha in 1979. The higher Mg accumulation in 1979 reflected greater total dry matter production and higher Mg concentrations in the various plant fractions. Total Mg accumulation also increased through pod fill, but declined near maturity because of leaf drop and petiole abscission. Irrigation increased total Mg accumulation by increasing leaf and petiole growth (Fig. 1). The effects of supplemental irrigation on the Mg concentration in the various plant fractions are also summarized in Table 4, but none of the differences were significant.

Analyses of Mg data also showed that except for the nonirrigated treatments in 1978, uptake of Mg during the vegetative and reproductive growth stages tended to be linear with time (Fig. 4). Similarity in uptake patterns between Ca and Mg were anticipated because Mg also moves primarily by mass flow.

Magnesium concentrations in the various plant fractions of each cultivar at selected growth stages are presented in Table 5. The stem fraction was the only plant part which had significantly different Mg concentrations. Stems from the cv. Ransom had the highest Mg concentration at all 1978 sampling dates, but the lowest concentration at the first sampling date in 1979. Subsequent samplings in 1979 showed no significant differences in the Mg concentrations within any of the plant fractions. Our Mg concentrations and the resultant accumulations were much greater than those reported by Henderson and Kamprath (1970), but at all sampling dates the Mg concentration in all plant fractions was relatively constant and within the sufficiency ranges reported by Small and Ohlrogge (1973).

The distribution of Mg (Fig. 4) shows that in 1979 accumulation in leaves, petioles, and pods was much greater during the reproductive stages than during 1978. This was probably the result of the entire soil profile being wetter and thus providing more Mg to the plant by mass flow. Our accumulation patterns for these 2 years support the earlier conclusion that Mg accumulation must occur at a substantial rate during pod fill.

## Seed Yields

Seed yields (Table 3) were not closely related to the total dry matter production or the total amount of K, Ca, or Mg accumulated. With irrigation during the short-term drought of 1979, seed yields were much lower than the irrigated soybean yields in 1978. A large number of factors including a lower plant density and possible $O_2$ stress during pod fill may have contributed to the lower yields in 1979, but the K, Ca, and Mg concentrations and levels of accumulation do not appear to have been the yield-limiting factors in either year.

## SUMMARY AND CONCLUSIONS

These data are useful in identifying the accumulation and distribution of dry matter, K, Ca, and Mg in selected cultivars of determinate soybeans grown on Norfolk loamy sand with and without irrigation. They show that irrigation did not significantly change the K, Ca, and Mg concentrations within the soybean plants, although total accumulations were generally greater because of increased plant growth. Changes in cation concentrations between years may have reflected differences in nutrient availability in the soil solution, since the seasonal weather patterns were quite different. Analyses showed that the uptake of K, which moves by diffusion, was influenced by drought more than the uptake of Ca and Mg which move by mass flow. Calcium and Mg accumulations were reduced only when plants were severely stressed by drought, but short-term drought influenced K accumulation in the soybean plants. Dry matter accumulations, nutrient concentrations, and nutrient accumulations among the cultivars studied in these experiments were generally statistically nonsignificant, although Ransom frequently had the highest nutrient concentrations and produced the highest seed yield.

## LITERATURE CITED

1. Bachelor, J. T., and H. D. Scott. 1979. Effects of irrigation on nitrogen and potassium uptake by soybeans. Arkansas Farm Res. 28:5.
2. Campbell, R. B., and C. J. Phene. 1977. Tillage, matric potential, oxygen and millet yield relations in a layered soil. TRANS. of the ASAE. 20:271–275.
3. DeMooy, C. J., J. Pesek, and E. Spaldon. 1973. Mineral nutrition. *In* C. B. Caldwell (ed.) Soybeans: Improvement, production, and uses. Agronomy 16:267–352. Am. Soc. of Agron., Madison, Wis.
4. Doss, B. D., R. W. Pearson, and H. T. Rogers. 1974. Effect of soil water stress at various growth stages on soybean yield. Agron. J. 66:297–299.
5. Fehr, W. R., C. E. Caviness, D. T. Burmood, and J. S. Pennington. 1971. Stage of development descriptions for soybeans, *Glycine max* (L.) Merrill. Crop Sci. 11:929–931.
6. Hammond, L. C., C. A. Black, and A. G. Norman. 1951. Nutrient uptake by soybeans on two Iowa soils. Iowa Agric. Exp. Stn. Res. Bull. 384.
7. Hanway, J. J., and C. R. Weber. 1971. Dry matter accumulation in soybean (*Glycine max* (L.) plants as influenced by N, P, and K fertilization. Agron. J. 63:263–266.
8. Henderson, J. B., and E. J. Kamprath. 1970. Nutrient and dry matter accumulation by soybeans. North Carolina Agric. Exp. Stn. Techn. Bull. 197.
9. Isaac, R. A. 1977. Laboratory procedures for the soil and plant analysis laboratory. Georgia Exp. Stn., Athens, Ga.
10. Karlen, D. L., R. Ellis, Jr., D. A. Whitney, and D. L. Grunes. 1980. Influence of soil moisture on soil solution, cation concentrations, and the tetany potential of wheat forage. Agron. J. 72:73–78.
11. Marshall, C. E. 1977. The physical chemistry, and mineralogy of soils. p. 281, Vol. 2: Soils in place. John Wiley and Sons, Inc. NY.
12. Neunylov, B. A., and Y. I. Slabko. 1968. Utilization of nitrogen from fertilizers applied at various times. Agrokhimiya 12:3–9. (R)
13. Oliver, S., and S. A. Barber. 1966. An evaluation of the mechanisms governing the supply of Ca, Mg, K, and Na to soybean roots (*Glycine max*). Soil Sci. Soc. Am. Proc. 30:80–86.
14. Raper, C. D., Jr., and S. A. Barber. 1970. Rooting system of soybeans. II. Physiological effectiveness as nutrient absorption surfaces. Agron. J. 70:585–588.
15. Scott, H. D., and D. W. Brewer. 1980. Translocation of nutrients in soybeans. Soil Sci. Soc. of Am. J. 44:566–569.
16. Small, H. G., Jr., and A. J. Ohlrogge. 1973. Plant analysis as an aide in fertilizing soybeans and peanuts. *In* L. M. Walsh and J.D. Beaton (ed.) Soil testing and plant analysis. Soil Sci. Soc. of Am., Inc., Madison, Wis.
17. Steel, R. G. D., and J. H. Torrie. 1960. Principles and procedures of statistics. McGraw-Hill Book Co., Inc. N.Y.
18. Terman, G. L. 1977. Yields and nutrient accumulation by determinant soybeans as affected by applied nutrients. Agron. J. 69:234–238.
19. Viets, F. G., Jr. 1967. Nutrient availability in relation to soil water. *In* R. M. Hagan, H. R. Haise, and T. W. Edminster (ed.) Irrigation of agricultural lands. Agronomy 11:458–471. Am. Soc. of Agron., Madison, Wis.