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Growth and Nutrient Uptake by Soybean Plants in Nutrient Solutions of Graded Concentrations

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ABSTRACT

Soybean plants (*Glycine max* L. Merr. var. Hawkeye), grown in nutrient solutions maintained at graded concentrations showed a large response in both shoot dry weight and total ion uptake. Growth rate was dependent upon nutrient concentration, even when quantity of nutrient was not limiting. Peak periods for absorption of specific ions at certain growth stages were not exhibited. Rates of ion uptake by soybeans were generally proportional to the growth rate during the period of major growth. It is suggested that a dilute nutrient solution could provide sufficient nutrients for adequate root growth prior to major shoot growth, at which time a more concentrated nutrient solution is needed.

Research on plant nutrition generally falls into two classes. Most laboratory experiments have been short term excised root studies to examine the kinetics of the initial uptake processes (6, 7). Most greenhouse and field experiments have been more concerned with the final yield and plant composition than with the uptake patterns during the season. However, the needs of today require us to manage our crop systems not only to obtain maximum yield and nutrient use efficiency, but to do it with a minimum of environmental pollution by excessive fertilizer applications.

Successful management requires the supplying of the correct amount of nutrients to the plants at a time when they can best use them. This means we need basic plant physiological knowledge on the nutrient requirements of plants at various stages of growth. Loneragan (8) has discussed the confusion in the use of the term "nutrient requirement." It has been used to describe the concentration of nutrients in the solution in which the plant is growing and also the nutrient content of the plant at optimum growth. Whereas our primary interest is in determining the minimum solution concentration of a nutrient that permits maximum yield, the nutrient content of the plant is important in understanding the response of the plant to different nutrient levels.

The soybean was chosen as the experimental plant. It is considered to be one of the most important crops, yet its mineral nutrition is poorly understood. One would suspect that the nutrient uptake pattern of the whole plant would change with different stages of growth because the nutrient contents of the roots, stems, leaves, and fruit are all different. A comprehensive study (4) that combines years of field experiments indicates that potassium uptake peaks when the beans start filling. It is possible that other peak uptake periods were obscured by a variable nutrient supply.

Not only is the concentration of the nutrient supply important, but the ratios of the nutrients also modify the uptake pattern in most plants (1, 3, 9, 10). The number of treatments necessary to study both the concentration and ratio of nutrients is beyond the scope of this study. Therefore, the ratio of nutrients in the popular Hoagland's solution No. 1 (5) was chosen as a beginning point. The experiments reported in this paper were conducted to determine the nutrient uptake at various times during the growth cycle of soybeans supplied with graded concentrations of nutrients.

MATERIALS AND METHODS

Soybean seeds (*Glycine max* L. Merr. var. Hawkeye) were germinated by soaking in aerated distilled water for 6 hr followed by placement between moist paper towels. The radicle usually attained a 1-cm length by the end of 30 hr. For each treatment, six seedlings were selected for uniformity of radicle length and placed on cheesecloth stretched over the open bottom of a No. 10 plastic stopper. Seedlings were covered with moist filter paper and a watch glass until the roots protruded through the cheesecloth into 1 liter of nutrient solution.

Nutrient solutions were the No. 1 Hoagland solution (5) and the one-tenth, one-fourth, one-half, and three-fourth dilutions. Full strength of this solution has the following composition of major nutrients: 1 mM KH_2PO_4, 5 mM KNO_3, 5 mM $Ca(NO_3)_2$, and 2 mM $MgSO_4$. This is a little higher concentration than used in another nutrient study (9). The micronutrients were held constant for all variations in the above solutions. These were added as follows: 5 μM B, 0.9 μM Mn, 0.8 μM Zn, 0.03 μM Cu, 0.01 μM Mo. Iron was added as ferric EDTA to a level of 0.9 μM Fe. These levels are one-tenth of the recommended Hoagland solution, because a full strength of this solution resulted in toxic symptoms in preliminary experiments. There was no evidence that the levels used were not adequate.

Soybean plants were placed in the various solutions after germination between moist paper towels. Solutions were changed at least once daily to prevent more than a 10% change in concentration. In some cases, when the growth rate was high, 4-liter containers were used. The pH remained within 0.3 unit of the initial value of 5.5. The light chamber was on a

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15-hr day at a light intensity of 2000 ft-c. The temperature of the chamber was maintained at 27 ± 2 C day and night.

Each treatment was replicated four times. This gave yield and total uptake data that were within ±12% of the mean.

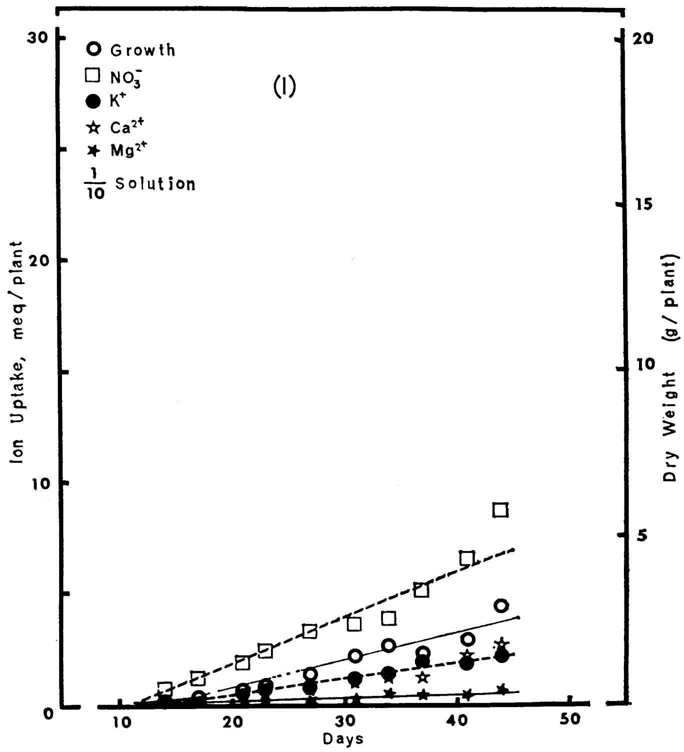

FIG. 1.

FIGS. 1, 2, 3, and 4. Soybean shoot growth and nutrient composition with time in four levels of Hoagland's solution.

Values reported in the graphs are averages of the four replications.

The treatment period was terminated by removing all six plants from a container and separating the shoot and root at the transition zone. Roots were rinsed four times with distilled water to remove the nutrient solution. Shoots and roots were transferred to paper bags and placed in a 60 C oven for 24 hr. This dry weight was used to express the plant yield for a particular treatment. The dried samples were ground in a Wiley mill to pass a 20-mesh screen.

Inorganic cation analysis was completed on plant material after it was heated in a muffle oven to 480 C for 2 hr. The ash was dissolved in 20 ml of 0.1 N HNO_3 and 10% acetic acid solution. Cation content was determined by atomic absorption spectrophotometry (2).

Total nitrogen, determined by the Kjeldahl procedure, was used as a measure of nitrate uptake since nitrate was the only nitrogen source.

RESULTS

Attempts to grow plants in a full strength Hoagland solution were not successful. Plants in this solution appeared to grow normally for the first 10 to 14 days, but at the 18th day their internodal length was relatively shorter than plants growing in other solutions and their leaves were yellow. On the 25th day when the lower leaves had begun to drop and a general yellowing of the entire plant occurred, this treatment was discontinued. Some plants recovered from these symptoms when the solution concentration was reduced.

The data are presented as the milliequivalents of nutrient ions in the shoot (Figs. 1–4) or roots (Fig. 5) per single plant during the growth period. Dry matter production is found from the right ordinate for the identical growth period.

Plants grew relatively slowly at first, and sufficient plant

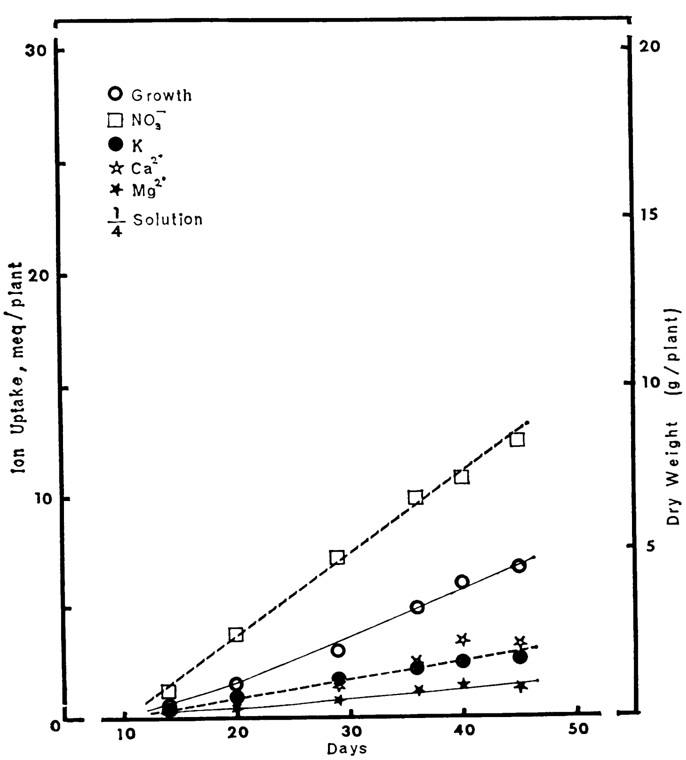

FIG. 2.

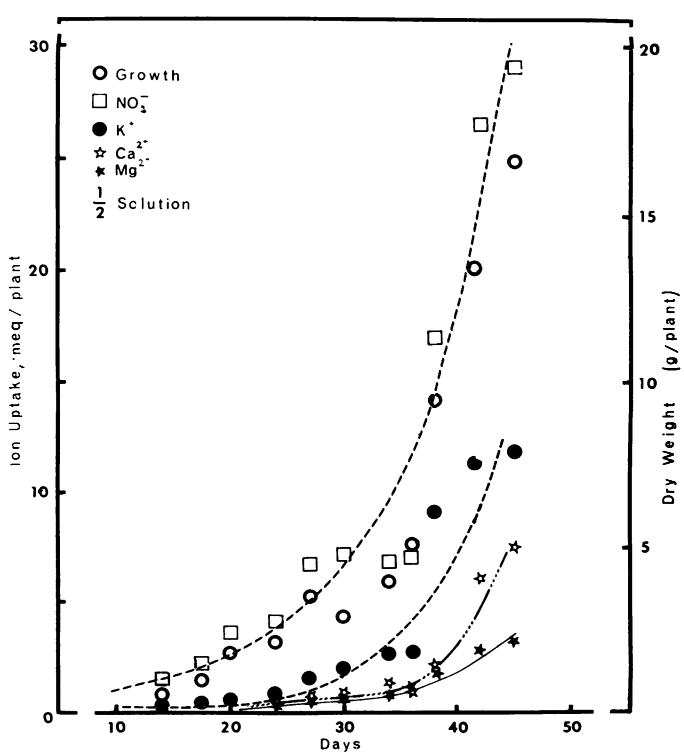

FIG. 3.

material for chemical analysis was not available until the 14th day. The nutrient concentrations of dry shoots at this time are given in Table I. There were only small differences in the growth of the plants in the different solutions up to 30 days. At this time the shoot growth in the half-strength solution became exponential and produced the maximum growth. The concentrations of nutrients in the plants in the different solutions changed somewhat until the 30th day, after which they remained essentially constant at the levels given in Table I. Half or more of the growth in all the treatments occurred while the nutrient concentrations in the plant remained constant. This means that nutrient uptake is closely connected to growth during much of the season.

The less than exponential growth of the plants in the solutions other than the half-strength is considered to be the result of nutritional stress. The soybeans must have been sensitive to the salt level in the three-fourths strength solution, although there were no visual symptoms. The response of the plants in the tenth- and quarter-strength solutions confirms the generally held hypothesis that the concentration as well as the capacity of the solution to supply nutrients is important in the nutrition of plants.

While the shape of the growth curve was greatly affected by the concentration of the nutrient solution, the stages of physiological development occurred at about the same time for all plants. For example, the first trifoliolate leaf was unrolled by the 15th day. The plants began to bloom by the 25th day with pod development following in a few days. Beans were filling the pods at the last harvest. The greatly shortened time scale for plant development compared to other studies (4, 9) is considered to be the result of the light and temperature regime used.

Nutrient solution concentration affected the shoot growth and nutrient content of the shoot but not of the roots. The growth and uptake by all roots were similar and are represented by one set of data in Figure 5. The greatest root growth did

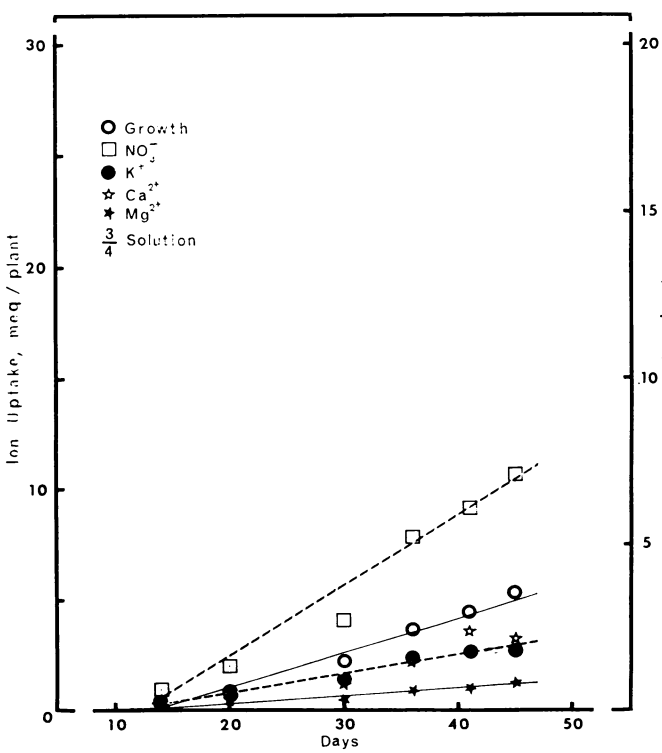

FIG. 4.

Table I. *The Nutrient Concentrations in Soybean Shoots Grown in Four Dilutions of Hoagland's Solution at the First Trifoliolate Leaf Stage and Averaged for the Stages After the Start of Pod Formation*

Dilution	N	K	Ca	Mg
	meq/g dry wt			
First trifoliolate leaf stage (14 days)				
One-tenth	4.14	0.96	0.45	0.15
One-fourth	4.35	0.97	0.65	0.21
One-half	4.84	1.03	0.64	0.28
Three-fourths	5.14	1.34	0.60	0.28
Averaged for the stages after pod formation (30–43 days)				
One-tenth	2.10	0.62	0.56	0.18
One-fourth	2.86	0.70	0.76	0.32
One-half	3.51	1.29	0.75	0.32
Three-fourths	3.38	0.88	0.83	0.29

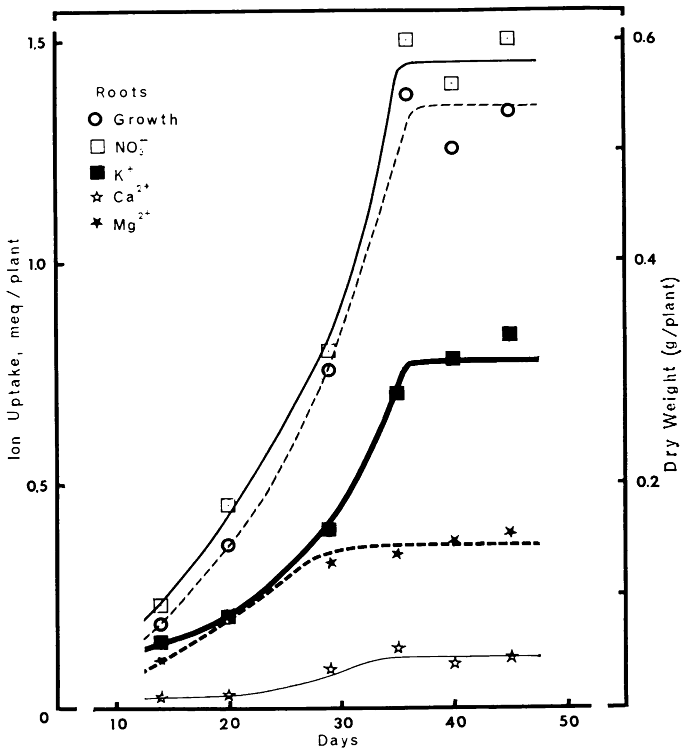

FIG. 5. Representative soybean root growth and nutrient composition with time in a nutrient solution.

occur in the half-strength solution, but the final dry weight was only about 50% larger than that for roots in the other solutions. The scatter of the data prevents a clear-cut pattern, but it is reasonable to expect the root system to reach some maximum size and then level off. The data from these experiments suggest that this occurred between 28 and 35 days under the conditions of this experiment.

DISCUSSION

The growth and nutrient composition of the aerial parts of plants depend upon several environmental factors. We attempted to keep constant most of these factors, including the ratio of the major nutrients. Without frequent changes of the nutrient solution, both the concentration and ratio of nutrients change with time.

Although the plants were exposed to an unlimited nutrient supply, the cells did not accumulate these ions to unusual levels. This is in agreement with the findings of de Wit *et al.* (10), who observed that plants grow at a rate correlated with the plant organic acid level established to balance the excess cation content. The growth and nutrient composition of the plants grown on the one-fourth and three fourths-strength solutions were similar. In addition the 4-fold increase in growth by the plants in the one-half-strength solution was accompanied by a major change only in the potassium content. In general, nitrogen concentration in the plants was affected by the solution strength much more than the cation constituents. However, in all cases it was much larger than the sum of the measured cations (Table I).

The accumulation of nitrogen, potassium, and calcium by roots is proportional to growth and constant concentrations of about 2.9 meq N, 1.3 meq K, and 0.24 meq Ca per gram of dry roots are maintained. Magnesium concentrations of the roots decreased from 1.1 meq/g at 14 days to 0.7 meq/g in the mature root. This is still much larger than the concentrations in the shoot (0.2–0.3 meq/g).

The similarity of root growth and uptake over the 7.5-fold nutrient concentration range indicates that meeting the root requirements is not sufficient for maximum shoot growth. In fact, a solution maintained at one-tenth strength might be sufficient for the roots. The root-shoot interrelations can be further illustrated by noting that the major increase in the shoot growth in the one-half strength solution occurred after 30 days. A full root system is apparently needed to support the rapid shoot growth.

It was anticipated that a larger demand for a particular nutrient at some stage of growth would be reflected in an inflection point on the uptake curve for that nutrient. Such an inflection point is not obvious in the data. At the final harvest, the beans were already formed and were filling the pods. After this stage of growth, a decreased rate of uptake is expected as the plant matures.

The data in Table I show that the concentration of potassium in the plants growing in the optimum half-strength solution increased after the first trifoliolate leaf stage whereas the potassium concentration of plants growing in other solutions decreased. Evidently plants under optimum conditions have a demand for potassium above that required for growth up to 30 days. This is understandable since it has been postulated (3) that potassium cycles between the nitrate translocated upward and organic acids translocated downward.

A most important time in soybean development appears to be the start of pod formation. This occurred at about 30 days in these experiments. Soon thereafter (36 days) roots ceased growing, although the rate of shoot growth was accelerating, and the nutrient concentrations in the root reached a plateau.

These experiments suggest the following developmental and nutritional questions that have important practical implications. Does root growth reach its maximum before the exponential stage of shoot growth? If so, can adequate root growth be obtained with lower nutrient concentrations than those required for the later optimum shoot growth? Perhaps the ratio of cations would have to be adjusted to favor magnesium over calcium during this period. The practical implication is that in the farming situation nitrogen fertilizers may be leached away from the roots before the plants can make best use of them.

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