AVAILABLE CALCIUM A FACTOR IN SALT BALANCE FOR VEGETABLE CROPS[1]

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The availability of calcium in a soil has a tremendous effect on the quality of growth of vegetable crops. The type of fertilizer materials which are used for the growth of vegetable crops and the manner in which the soil should be handled depend on the potential calcium supply. Vegetable crops differ widely, and even varieties differ in their nutrient requirement with respect to available calcium. Fertilizer residues have a marked effect on exchangeable and available calcium as well as on the reaction of light cultivated soils. Observations made on vegetable farms in New Jersey, located on the sandy soils, show that pH is not always a reliable indication of the available calcium and that many of these sandy soils which have pH values[3] of 6.0 to 6.6, where large applications of soda and potash have been made, may be very deficient in calcium and magnesium. For acid soils or soils that have not received heavy applications of inorganic fertilizers the reaction test is a fairly reliable index of lime requirement. Cultivated soils on which liberal quantities of chemical fertilizers have been used, however, require a specific calcium test which should be interpreted on the basis of soil type and exchange capacity to indicate reliably the need for calcium.

Crops grown on soils having a high pH but a low available calcium supply respond differently to available soil moisture from those grown on soils having a more favorable nutrient balance. Observations on crops during several years of dry weather showed that the degree of injury varied with different farms even though soils were very similar in type. Truck crops on dairy farms where manure was used showed much less injury during dry weather than did those on farms where certain chemical fertilizers were used. Of the growers using all inorganic fertilizers some fared better than others. Those growers

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[3] All pH values quoted in this paper were determined either by the hydrogen electrode or by the Hellige Klett colorimeter.

who were following a fertilizer program of lime and acid-forming fertilizers were growing better crops during dry weather than were those who used acid fertilizers without lime or those who used a neutral fertilizer in which neutrality was brought about by other means than lime. It was common to find a luxuriant growth of vegetable crops on some farms as long as moisture was fairly well distributed, but to find those same crops very badly damaged during short periods of dry weather. In many cases there were differences in color of foliage and type of growth which could not be associated with any nutrient deficiencies. Similar symptoms were noticed on greenhouse tomatoes and cucumbers where an attempt was made to control the moisture supply. Greenhouse growers have to contend with a wide range of weather conditions because they grow crops the year around. The type of growth of plants grown in the greenhouse can be regulated to a great extent by controlling the water supply. Crops growing on dry soil very quickly indicate whether the soil solution is in good condition for optimum growth because, if the nutrients are not properly balanced, deficiency symptoms for certain nutrients may be encountered even though there is an abundant potential supply of a particular nutrient present. In view of the fact that available calcium has played such a large part in correcting greenhouse soil problems a number of preliminary experiments were conducted to study the relation of available calcium to type of growth principally of cucumbers, tomatoes, and lima beans, and a few other crops such as onions, celery, and carrots.

LOW CALCIUM SOILS AND THE RESPONSE OF PLANTS TO THE ADDITION OF CALCIUM SALTS

Soils from farms on which problems existed, but where the reaction of the soil seemed satisfactory, were brought to the greenhouse, placed in pots, and treated with various chemicals. Seeds or plants of certain crops were then planted in them. In practically all such cases, the soils were brought to the greenhouse because crops did not respond to side-dressings of ammonium sulfate or sodium nitrate; or if there was a response, the type of growth was unsatisfactory and the harvested crop was of poor quality. Poor germination of lima beans; crooked, poorly filled string beans; brown roots on most crops; rough rooted carrots; burned heart leaves of celery; light green spots on celery leaves; onions that did not keep well when harvested; and tomato fruits that did not ship well because they were too soft, were common symptoms. Usually when the marketable crop was of poor quality, the foliage also had certain peculiar symptoms which were not particularly characteristic of those caused by extreme deficiencies.

These soils were tested by means of the quick soil tests, as recommended by Hester (2), and were supplemented in some cases with microchemical tests on the plant tissue. These tests showed a low amount of available calcium (less than 100 p.p.m.—a few cases indicated a negative test) but the usual moderate amounts of all of the fertilizer nutrients present in a mixed fertilizer.

Very often high concentrations of potassium were found, or if potassium was not high, it was assumed from the growers' practice and a high pH reading that sodium probably was present in liberal amounts even though the concentration was not determined.

The technique in these soil pot cultures was to supply sodium nitrate, calcium nitrate, calcium chloride, calcium carbonate (limestone), superphosphate, gypsum, and in some cases potassium nitrate, dolomite, and calcium-magnesium silicate slag to separate pots as a preliminary trial. Growth of the plants was then observed. Usually the results of the preliminary trial were sufficiently convincing to warrant the making of recommendations. Where the problem involved a calcium deficiency, the more soluble calcium salts gave a better response than those having a lower solubility. Calcium nitrate was highly effective. If the pots were kept well watered, superphosphate proved very beneficial, and gypsum was satisfactory. If the soil was kept quite dry, calcium nitrate gave a very good correction, but calcium sulfate was ineffective. Superphosphate was effective but not so effective as calcium nitrate. One difficulty with calcium nitrate was the necessity of supplying it at 3-week to monthly intervals to obtain best results. Dolomitic limestone usually gave very good results, and the correction was usually better than with calcium carbonate.

On these calcium-deficient soils sodium and potassium nitrate had depressing effects on growth, the degree of injury (unless some form of calcium was supplied with it) depended on whether the soil had abundant potassium or whether in the past it had been supplied with comparatively large amounts of sodium nitrate.

LOW CALCIUM-HIGH POTASSIUM SOILS AND PLANT GROWTH

One of the experiments on plant growth involving a greenhouse soil containing low calcium and high potassium is given as an example.

Cucumbers when freely watered in the greenhouse made a rapid growth in certain sections of the beds but were not normal. The internodes were long, probably as a result of the large amounts of water needed to grow the crop. The foliage was light green, and the leaves were small. They were grown on strings up to wires 7 feet above the soil. When the growing tip reached the wire, many of the veins of the older leaves showed a brown, water-soaked condition, which was soon followed by dying and gradual drying of the whole leaf, with the result that the plants soon had only the tip leaves left. Mosaic-like symptoms were present and were associated with malformed growing tips and leaves. After it was decided that mosaic was not the cause[4] the plants were examined microchemically. The tissue in question was packed with potassium and nitrate, but calcium was entirely lacking. The roots were kinky and rough, and the cortex had sloughed off prematurely.

[4] Dr. S. P. Doolittle of the U. S. Department of Agriculture examined these plants and said there was no mosaic present, but that the disturbance resembled a nutritional one.

Tomatoes growing in another house were tested, and similar observations were made. The tomatoes were growing much better and were fruiting but were not making a desirable growth; it was apparent that they were being affected by a similar nutritional disorder. The foliage was dotted with light green spots.

A quick chemical test (2) showed a pH range of 5.8 to 6.6.[5] Less than 50 p.p.m. of calcium was present. Potassium was exceptionally high and fluctuated with the water supply. As soon as a test could be made after a heavy application of water, the potassium was found to be very low but just before water was again applied, when the soil was quite dry, the potassium concentration was found to be very high. Apparently very little of the potassium was in the colloid and was easily leached to lower levels. The phosphorus concentration was approximately 70 p.p.m. Only a trace of magnesium was found, but the nitrate concentration was high. The soil baked very hard when dry and was very slippery when wet. It was classed as a medium sandy loam of a grayish black appearance although organic matter was comparatively low. A hardpan from one-half to 2 inches thick had formed under the plow depth, although drainage was satisfactory in most cases. This soil had been in use for 16 years.

The result of these observations indicated that a deficiency of calcium or magnesium or both was causing the symptoms. The roots resembled those of plants growing with insufficient calcium. The symptoms exhibited by the tops, however, did not resemble those of calcium or magnesium deficiency insofar as they were known. A macrochemical test of the soil was made. The soil colloid was found to be approximately 87 per cent calcium and 2 per cent magnesium saturated. The calcium content in the $6\frac{2}{3}$-inch acre depth was estimated to be equivalent to 7 tons of ground limestone. The potassium content was equivalent to 3.4 tons of muriate of potash.

Soil was taken from the poorest section of the beds, placed in 8-inch pots, and treated with individual salts. A cucumber plant was set in each pot. The amount of material applied, consisting of individual salts in each case, was equivalent to what would be found in a ton of 5–8–7 fertilizer or a ton of hydrated dolomite. The pots were watered just enough to prevent wilting.

Data from the pot cultures showed that soluble calcium salts gave a normal type of growth when compared with that of the injured plants grown in soil with no treatment. Calcium nitrate and calcium chloride were more effective than calcium sulfate. Plants grown with additional superphosphate, indicated some correction. It was later noticeable that calcium sulfate and superphosphate were more effective when the soil was kept more freely watered.

[5] The water used in this range came from wells and contained considerable sodium chloride and some calcium chloride. Records showed a pH reaction several years back of 7.6 to 8.4. The water was later taken from a brook, and a fertilizer mixture of ammonium sulfate, potassium sulfate, and superphosphate was used to lower the pH. This treatment had lowered the pH when the soil was examined for this experiment.

Plants grown with sodium or potassium salts gave no response or were injured when the sulfate ion served as the carrier. This injury was very characteristic of that found in the greenhouse.

Roots on plants supplied with lime were very extensive and vigorous and, instead of growing toward the outside of the pot and between the walls of the pot and soil, as was the case where more soluble salts were applied, they were distributed all through the soil to the extent that the soil crumbled to pieces instead of coming out in a solid ball when the pots were dumped. This indicated a difference in aeration of the soil.

From these results it was apparent that the correction was brought about by the addition or greater availability of calcium, as is shown by the addition of potassium sulfate or chloride. The sulfate tended to decrease calcium availability, thereby producing a low calcium-high potassium condition to the extent that the potassium prevented calcium from being absorbed by the plants, as has been suggested by Lundgårdh (3). Apparently calcium sulfate was not sufficiently soluble in soils with low moisture content. The beneficial effect of calcium nitrate endured for 3 to 4 weeks, and repeated applications had to be made.

The relationship between calcium and potassium was repeated in sand culture. It was found that as long as calcium was maintained at a high level (0.0090 p.v.m. conc. of 1 atmos. solution) it was impossible to injure the growth. If, however, the calcium concentration was maintained at a low level (0.0014 p.v.m. conc.) the effect of large amounts of potassium was to produce a type of growth that was not symptomatic of any particular deficiency but was soft and succulent, as though the plants were watery in texture, and the foliage had a yellowish green cast resembling plants that do not assimilate nitrate readily. A discussion of this whole problem, interpreting the relation of calcium to potassium has been given by Lundegårdh (3). As far as the effect of the relationship of calcium to potassium is concerned, these results agree with his observations.

As a result of these observations, a recommendation was made that 1 ton of dolomitic limestone be used per acre each year, unless the soil reaction test indicated otherwise, that calcium nitrate be used as the source of nitrogen and superphosphate as the source of phosphoric acid, and that potash be withheld until a test showed that it was needed. Spent mushroom manure, which added some potassium, was being used on the beds.

Two years after the treatment was recommended, the soil was examined. Crop growth was much improved, and the roots on both cucumbers and tomatoes were white and vigorous. A test showed the presence of sufficient available calcium and of potash in liberal quantities. The soil no longer baked when dry nor did it pack down so firmly as before. In the past, nematodes had been a problem and steam sterilization of the soil did not seem to eradicate the pest completely because it was difficult to get the hard clumps of soil heated through. At the present time, the soil heats through readily and thorough eradication is effected with much less heating. The excessive heating and the poor aeration of the soil in the past undoubtedly contributed to the poor growth, but apparently the correction of this soil depended on one of the many functions of calcium directly in the soil and indirectly on the plant growth.

The similarity of growth of vegetable crops on the coastal plain soils of New Jersey to the growth of plants observed in greenhouse soils prompted further experiments in sand and soil pot cultures to determine, if possible, how the chemical composition of the plant was changed by different ratios of available calcium to other cations. Some results on sodium are presented at this time.

TABLE 1

Partial volume molecular concentration of nutrient solutions used in determining the relation of calcium-sodium ratio to the growth of the tomato

SOLUTION*	KH_2PO_4	$MgSO_4$	$Ca(NO_3)_2$	$NaNO_3$†	$CaCl_2$	NaCl
A, 3 atmos.	0.0045	0.0045	0.0405	0.0045	....	....
B, 3 atmos.	0.0045	0.0045	0.0225	0.0225	....	....
C, 3 atmos.	0.0045	0.0045	0.0045	0.0405	....	....
D, 1.75 atmos.	0.0045	0.0045	0.0203	0.0023	....	....
E, 1.75 atmos.	0.0045	0.0045	0.0113	0.0113	......	....
F, 1.75 atmos.	0.0045	0.0045	0.0068	0.0156	....	....
G, 1.75 atmos.	0.0045	0.0045	0.0023	0.0203	....	....
H, 1.5 atmos.	0.00675	0.00235	0.02025	0.00235	....	....
I, 1.5 atmos.	0.00675	0.00235	0.00235	0.02025	....	....
J, 1.5 atmos.	0.00675	0.00235	0.00235	....	0.02025	....
K, 1.5 atmos.	0.00675	0.00235	0.00235	....	....	0.02025

* Concentrations are approximate and varied somewhat from values stated.

† The sodium nitrate furnished one-half as much nitrate as the calcium nitrate. This arrangement seemed necessary to keep calcium and sodium more comparable for purposes of this investigation. The same is true of the chloride content.

CALCIUM AND SODIUM RATIO AND GROWTH OF TOMATO IN SAND CULTURE

Studies on the effect of calcium and sodium ratio on plant growth were made on the tomato because of the various peculiar types of growth found in fields of canhouse tomatoes. A critical examination of the plants and of the soil showed that the problem was not one involving potassium because it was not being used in sufficiently large amounts to approach the concentrations which would produce abnormal growth of the foliage. Since growers, however, were using large amounts of sodium nitrate and very little calcium-carrying material, it seemed that a study on the effect of varying the calcium to sodium ratio on the growth of the tomato would be helpful as a guide to diagnosing peculiar growth conditions in the field even though the extreme ratios used in the pot cultures might not necessarily be encountered under field conditions.

Tomato plants were set in 3-gallon coffee urns in white, sifted, washed pit sand, and nutrients were applied by a continuous drip system. Eighteen-liter inverted bottles served as reservoirs to supply the nutrients to five crocks, by means of asphalt-coated $\frac{3}{4}$-inch pipe and small pieces of capillary tubing at each crock to regulate the flow so that 3 liters were supplied each crock during 20 hours.

The nutrient solutions used are given in table 1. Two lots of plants were grown.

Plants in lot 1 were grown from February 5 to March 5 with solutions A, B, and C. Solutions having an osmotic concentration of approximately 3 atmospheres pressure were used because, during this time of the year when much cloudy weather prevails, plants grown in a more concentrated nutrient salt medium produce a less succulent growth which is more comparable to that of plants grown with abundant sunshine. The initial plants placed in the crocks were 6 to 7 inches high, were high in carbohydrates and low in nitrates, and had

TABLE 2

Dry matter in organs of tomato plants grown with nutrient solutions containing different ratios of calcium to sodium

SOLUTION	STEMS		PETIOLES		BLADES	
	Lower	Upper	Lower	Upper	Lower leaves	Upper leaves
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Iintial plants*	20.6	....	11.9	....	19.1	....
A, 9 Ca–1 Na	17.5	11.7	11.3	10.5	14.2	14.9
B, 5 Ca–5 Na	16.3	10.8	10.6	10.1	12.6	14.5
C, 1 Ca–9 Na	16.2	9.4	9.5	8.6	10.7	13.3
D, 9 Ca–1 Na	7.1		7.0		12.7	
E, 5 Ca–5 Na	6.5		6.3		11.2	
F, 3 Ca–7 Na	6.1		5.8		10.1	
G, 1 Ca–9 Na	6.0		5.4		9.3	

* Plants supplied with solutions A, B, and C were grown from February 5 to March 5. Plants grown with solution D, E, F, and G were grown from March 6 to April 3.

a gray-green appearance. A composite sample for dry matter determinations was made on blades, petioles, and stems. When the plants in the crocks were harvested, the upper and lower blades, petioles, and stems were analyzed separately.

Plants in lot 2 were grown with solutions D, E, F, and G. They were 2 inches tall, were comparatively soft and succulent, were dark green in color, and contained appreciable amounts of nitrates, but little starch. They were set in the crocks on March 6 and harvested on April 3. The solutions used had an approximate concentration of 1.75 atmospheres, inasmuch as light conditions were more favorable than for the group 1 plants.

The data on percentage of dry matter for both lots are given in table 2, carbohydrate fractions in table 4, and nitrogenous fractions for plants in lot 2 in table 3.

Regardless of the part of the plant examined, the data from plants grown with solutions A, B, C, (table 2) show a decrease in dry matter as the proportion of calcium is decreased and sodium is increased from a ratio of 9:1 to 1:9.[6] For example, the old stems decreased 1.3 per cent, the old petioles 1.8 per cent, and the old leaf blades 3.5 per cent, whereas the upper stems (younger tissue) decreased 2.3 per cent, the upper petioles 1.9 per cent, and the younger leaf blades 1.6 per cent. The younger plants, which were more succulent, grown

TABLE 3

Nitrogenous fractions of different parts of tomato plants grown with solutions in which the ratio of calcium to sodium was varied

Data expressed as percentage of green and dry matter

SOLUTION	TOTAL ORGANIC N		PROTEIN N		SOLUBLE ORGANIC N		NITRATE AND AMMONIUM N	
	Green	Dry	Green	Dry	Green	Dry	Green	Dry
Tomato stems								
D, 9 Ca–1 Na	0.1401	1.90	0.0801	1.05	0.0600	0.85	0.0800	1.12
E, 5 Ca–5 Na	0.1041	1.60	0.0757	1.16	0.0284	0.44	0.0876	1.35
F, 3 Ca–7 Na	0.0974	1.62	0.0670	1.12	0.0304	0.50	0.0856	1.40
G, 1 Ca–9 Na	0.0800	1.33	0.0552	0.92	0.0248	0.41	0.0856	1.43
Tomato leaf blades								
D, 9 Ca–1 Na	0.6230	4.84	0.5278	4.09	0.0952	0.75	0.0424	0.33
E, 5 Ca–5 Na	0.5277	4.67	0.4301	3.80	0.0976	0.87	0.0424	0.38
F, 3 Ca–7 Na	0.4789	4.75	0.3833	3.80	0.0956	0.95	0.0564	0.56
G, 1 Ca–9 Na	0.4229	4.55	0.3497	3.76	0.0732	0.79	0.0700	0.75
Tomato leaf petioles								
D	0.1248	1.76	0.1004	1.41	0.0244	0.35	0.1692	2.41
E	0.0984	1.52	0.0762	1.17	0.0222	0.35	0.1498	2.39
F	0.0926	1.49	0.0726	1.14	0.0200	0.35	0.1400	2.41
G	0.0630	1.17	0.0516	0.96	0.0114	0.21	0.1406	2.60

with solutions D, E, F, and G likewise showed similar trends, decreasing 1.1 per cent in the stems, 1.6 per cent in the petioles, and 3.4 per cent in the leaf blades.

[6] The ratios of calcium to sodium used in these experiments are extreme to facilitate interpretation of data for narrower ratios. It is doubtful whether these extremes would be encountered on coastal plain soils of New Jersey except in special temporary cases where the potential supply of calcium in the soil was low and a heavy application of nitrate of soda had been made. A number of cases have been identified in the culture of late celery where a heavy rain was preceded by a heavy application of sodium nitrate. Under such conditions leaching was sufficiently severe to carry the replaced calcium out of reach of the feeding roots. Complete calcium deficiency symptoms have been observed under such conditions.

In the plants grown in the low calcium-high sodium treatment[7] there was a consistent decrease in assimilated organic nitrogen (table 3) while the mineral nitrogen (nitrate and ammonium) showed no significant difference except in the leaf blades where the nitrate content increased while protein nitrogen decreased.

The carbohydrates decreased (table 4), although not so consistently as did the organic nitrogen, as the ratio of calcium to sodium changed from 9:1 to 1:9. The largest difference was between the 9:1 and the 5:5 ratios. The weight of the plants in the various groups was very similar. The high calcium

TABLE 4

Carbohydrate fractions in the blades and stems of tomato plants grown with nutrient solutions in which different proportions of calcium to sodium ions were present

Data expressed as percentage of green matter

SOLUTION	REDUCING SUGAR		TOTAL SUGAR		STARCH		HEMICELLULOSE	
	Blades	Items	Blades	Stems	Blades	Stems	Blades	Stems
Initial plants	1.008	1.778	1.104	2.221	6.156	3.121	0.287	0.226
Upper blades and stems								
A, 9 Ca–1 Na	0.675	0.679	1.062	1.203	0.700	0.220	0.206	0.296
B, 5 Ca–5 Na	0.674	0.524	0.841	0.967	0.384	0.178	0.186	0.216
C, 1 Ca–9 Na	0.359	0.531	0.804	0.919	0.297	0.160	0.219	0.244
Lower blades and stems								
A	0.395	0.670	0.618	1.642	0.366	0.670	0.182	0.294
B	0.390	0.579	0.567	1.549	0.199	0.693	0.130	0.290
C	0.233	0.612	0.399	1.575	0.171	0.483	0.139	0.421
Total blades and stems								
D, 9 Ca–1 Na	0.340	0.265	0.692	0.414	0.296	0.085	0.152	0.226
E, 5 Ca–5 Na	0.196	0.171	0.491	0.343	0.146	0.093	0.146	0.190
F, 3 Ca–7 Na	0.076	0.177	0.136	0.262	0.064	0.054	0.089	0.154
G, 1 Ca–9 Na	0.086	0.183	0.140	0.260	0.140	0.063	0.049	0.141

plants were more uniformly dark green in color than the high sodium plants. The general appearance of the plants indicated a difference in concentration of soluble organic nitrogen. Even though the high and low calcium soultions contained different amounts of nitrate (made necessary by the substitution of monovalent sodium for divalent calcium) the concentration of nitrate in the plants was similar (table 3).

[7] The methods were the same as those used for chemical analysis of tissue described in the New Jersey Agricultural Experiment Station Bulletin 547, but modified to include the method of extraction suggested by Davidson et al. in *Plant Physiology* 9: 817–822.

CALCIUM: SODIUM RATIO AND GROWTH OF TOMATO WITH HIGH AND LOW NITRATE SUPPLY

Two lots of plants, each consisting of 60 crocks with 3 tomatoes in each, were grown in sand culture, one with solution D and the other with solution G (table 1). The plan was to shift these to other solutions when the plants were 12 to 15 inches high. Before the plants could be shifted, however, a mosaic disease made its appearance and killed the plants in 55 of the crocks supplied with solution G (high sodium) but did only slight damage to the plants grown in solution D (low sodium). Although this was not part of the experiment, it was a good indication that these experiments were producing a type of growth which was similar to, and fully as susceptible to weather conditions and disease as, that of many tomato plants growing in the fields which were low in available calcium. The watery, light green, succulent growth of the high sodium plants grown with solution G and the darker green, less succulent plants grown with the high calcium solution D, even though of the same size, were characteristic of types of growth associated with good and poor growing conditions in the field.

The experiment was repeated. Although the tomato plants in the two groups were very similar to the plants in the two previous groups, they grew free of mosaic. Two 4-inch seedling plants comparatively soft and succulent and dark green were placed in each of the crocks on January 20, one-half being supplied with solution H and the other half with solution I (table 1), until March 1 when they were 12 to 14 inches high. At this time the plants receiving solution H (high calcium) were dark green, succulent, and growing rapidly. The other plants grown with solution I (high sodium nitrate) were slightly larger but lighter green and seemed to be more succulent than the calcium group. They wilted more easily when the day temperature increased as a result of bright sunshine. On March 2 the 120 plants grown with solution H were divided into four groups. Group 1 was continued with the same solution; group 2 was given solution I (high sodium nitrate); group 3 was given solution J (high calcium chloride in place of calcium nitrate); and group 4 was given solution K (high sodium chloride).

The 120 plants grown with solution I (high sodium nitrate) were likewise divided and treated as the previous group.

The plants were harvested on March 11, 9 days after being shifted to different solutions. The short interval elapsing between the shifting of solutions and harvesting was necessary to prevent excessive hardening due to accumulation of carbohydrates in the low nitrate groups. This accumulation of carbohydrates overshadowed the assimilation of the nitrate ion and consequently tended to mask the cation effect. Only the stems were harvested and analyzed. They were divided into 10 inches of base and 6 to 10 inches of tip of stem tissue. The dry matter and the nitrogenous fractions are shown in table 5.

There was very little difference in percentage of dry matter in the base of the stems. In the upper portion of the stems, the results agree with those in table 2 in that there was 9.8 per cent dry matter in plants grown with sodium nitrate as compared with 11.0 per cent in those grown with calcium nitrate. The plants in the latter treatment, however, did not decrease in dry matter when shifted to sodium nitrate, as was expected; but the sodium nitrate plants did increase in dry matter when shifted to calcium nitrate, as was expected. When either group was shifted to the low nitrate solutions, carbohydrate accumulation apparently increased the dry matter still further. This increase was accentuated more by sodium chloride than by calcium chloride, apparently because nitrate assimilation is at a lower level where sodium is increased. This permits carbohydrates to accumulate more rapidly than where calcium is maintained at a higher level.

TABLE 5

Dry matter and nitrogenous fractions in the lower and upper stems of tomato plants after being shifted from one nutrient solution to another

SOLUTION* CHANGE	DRY MATTER		NITRATE N		SOLUBLE ORGANIC		PROTEIN N		TOTAL ORGANIC N	
	Lower stem	Upper stem	Lower stem	Upper stem	Lower stem	Upper stem	Lower stem	Upper stem	Lower stem	Upper stem
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
H to H	7.0	11.0	0.0817	0.0866	0.0829	0.1034	0.0828	0.1147	0.1757	0.2181
H to I	7.0	11.5	0.0821	0.0807	0.0503	0.0901	0.0888	0.1065	0.1391	0.1966
H to J	7.2	12.1	0.0369	0.0389	0.0475	0.0778	0.0905	0.0976	0.1380	0.1754
H to K	7.2	12.3	0.0457	0.0331	0.0563	0.0917	0.0743	0.1027	0.1306	0.1944
I to I	7.0	9.8	0.0739	0.0807	0.0553	0.0653	0.0805	0.0987	0.1358	0.1640
I to H	7.0	11.0	0.0866	0.0816	0.0734	0.1028	0.1081	0.1236	0.1815	0.2260
I to J	7.0	11.1	0.0428	0.0273	0.0502	0.0847	0.0750	0.1035	0.1252	0.1882
I to K	7.0	13.0	0.0321	0.0369	0.0657	0.0719	0.0814	0.1057	0.1471	0.1776

* Composition of nutrient solutions given in table 1 (H = high calcium nitrate, I = high sodium nitrate, J = high calcium chloride, K = high sodium chloride).

The data on nitrogenous fractions are in better agreement with those given in table 2 than are dry matter determinations. Soluble organic nitrogen was much higher in the calcium nitrate plants than in the sodium nitrate plants. This is shown by the comparison between groups H and I. Where H was shifted to I, amino acids decreased, but where the shift was made from solution I to H amino acids increased. This holds as long as there was sufficient nitrate nitrogen present to prevent carbohydrate accumulation. The difference in amino acids was greater when the plants were shifted from solution I to H than from solution H to I. Had the plants been grown for a longer period on the shifted solutions, it is probable that even the H to I (Ca to Na) shift would have shown a greater difference. The protein nitrogen shows similar trends, although the differences were not so great as in the more quickly assimilated amino acids.

DISCUSSION

The importance of calcium in the nutrition of plants has been shown by Prianischnikov (6) and by Nightingale et al. (5). The importance of the calcium ion as an antagonizer of all other cations necessary for plant growth has likewise been shown (7). The data and observations presented in tables 2 to 5

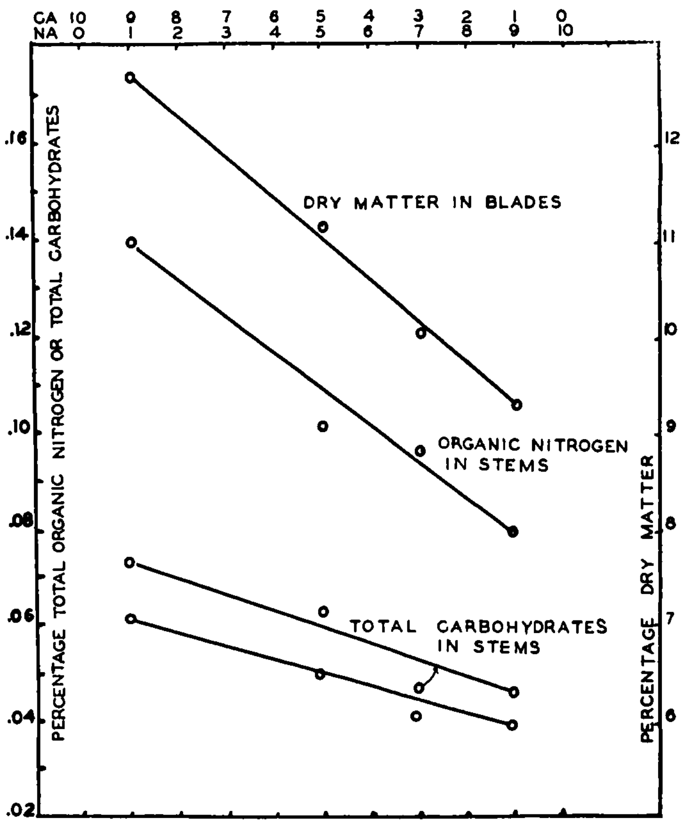

FIG. 1. EFFECT OF DIFFERENT RATIOS OF CALCIUM TO SODIUM ON DRY MATTER, ORGANIC NITROGEN, AND CARBOHYDRATE FRACTIONS IN TOMATO

inclusive further emphasize the importance of the calcium ion in regulating the growth of the plant.

Plants grown with an optimum supply of calcium apparently are dark green, possess a composition that is resistant to changes in environment, and present few physiological disorders because they assimilate nitrogen and carbon most rapidly. Even though the plants in the two groups, one grown with an optimum calcium supply and the other grown with a similar cation supply but comparatively low in calcium, made an equal volume of growth, but the quality of growth was vastly different. As the calcium content in the nutrient solution decreased and the sodium increased, the tissue contained more water. Under conditions of rapid transpiration (lowered relative humidity) the high calcium plants showed no signs of wilting, whereas the low calcium plants wilted severely. In these cultures the ratio of calcium to sodium was not low enough to cause injury to the roots or to cause proteolysis as was suggested by Nightingale (5) in the case where calcium concentration was too low to support synthetic processes. In figure 1 are shown trends for dry matter, organic, nitrogenous, and carbohydrate fractions from plants grown with different amounts of calcium. A decrease in calcium is accompanied by a decrease in synthesized products. Were the curves extended to the point where there was no longer sufficient calcium to support synthetic processes, organic nitrogen would probably decrease but carbohydrates would increase rapidly for a short period until proteolysis disintegrated the carbohydrates more rapidly than they were being synthesized.

The difference in water content may be explained by the difference in affinity for water by calcium and sodium ions, as was pointed out by Flint (1). Mattson (4) has shown a difference in dispersion due to hydration of proteins when associated with calcium or sodium ions. It would seem possible that there are certain associations between sodium and proteins in the cell which would require the presence of more water. The dehydrating effect of the calcium ion introduced into such a system would tend to counteract or antagonize the effect of the sodium. In view of the fact that potassium has a similar effect to sodium, although to a smaller degree, it is entirely possible that one of the functions of potassium when absorbed is to counteract the dehydrating effect of an over-abundance of calcium.

From these results it would seem that a very important function of calcium is to hold the cell protoplasm in an equilibrium conducive to synthetic processes that build up proteins rapidly. This accumulation of proteins in turn gives stability to protoplasm, the amount of calcium needed for optimum synthesis being determined by the heredity of the plant. Thus plants which require a high pH likewise require a high calcium supply. A high soil pH brought about by ions other than calcium is not suitable because the physical properties when absorbed by the plant do not support synthetic processes as well. Thus the tomato which has a lower calcium requirement than the lima bean is less sensitive to soil conditions and tolerates a wider range of ratios than the lima bean, which makes very poor growth on soils that have a low calcium but otherwise high cation content. Many of our leguminous crops synthesize large amounts of proteins and also have a high calcium requirement.

A high proportion of protein to soluble organic nitrogen determines a certain quality (color and hardness) of growth. A high percentage of organic nitrogen means more dry matter and less water, or more substance to a given volume of growth. It is a common observation that spinach grown on a well-limed soil has a certain quality about it that prevents it from becoming yellow in color and soft in texture after a heavy rain. The grower who does not use much lime complains of losing a crop of spinach because of a heavy rain. A comparison of spinach from a well-limed and a poorly limed field shows the difference in texture. Celery will wilt, turn yellow, and die following a heavy rain on soil low in calcium but freely supplied with other cations. The importance of the ratio of calcium to other cations, which probably is the cause of many of our nutritional problems on the coastal plain soils, cannot be over-estimated. The effect it has on the quality of growth makes it possible to blame much of our quality problems on the lack of available calcium (changing of ratio of ions) in the soil solution, particularly since its availability may vary between conditions of drought and abundant rainfall.

From the results presented in the discussion on the relation of the calcium to sodium and potassium ion it is safe to assume that even though sodium is not important as a nutrient for plant growth it probably has a marked effect on plant growth and is worthy of serious consideration in our fertilizer practices. It also offers a clue to the advantages and disadvantages of different nitrate carriers on different types or soils containing different proportions of cations.

SUMMARY

Soil and sand culture experiments are reported which show that soils may have a satisfactory reaction for crop growth but have too little available calcium for optimum synthesis of protein and carbohydrate materials.

An abundance of potassium may prevent the absorption of sufficient calcium on media low in calcium.

Plants grown with a ratio of 1 part calcium to 9 parts of sodium had from 1 to 3 per cent less dry matter than did plants grown with 9 parts of calcium and 1 part of sodium.

Associated with this decrease in dry matter, there was a poorer type of growth, which made plants more susceptible to wilting, to certain constitutional disorders, and to severe injury during periods of drought or heavy rainfall.

The ratio of available calcium to potassium or sodium was extremely important for germination of seed and growth of vegetable crops on coastal plain soils.

It is suggested that the effect of cations on growth is due to the hydration of protoplasm induced by different cations.

Nitrate-carrying salts apparently have other functions in the plant than merely supplying the necessary nitrogen for growth, a fact worthy of consideration in fertilizer practices.

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