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Calcium Deficiency in Sorghum Grown in Controlled Environments in Relation to Nitrate/Ammonium Ratio and Nitrogen Source

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ABSTRACT

Sorghum [*Sorghum bicolor* (L.) Moench] grown under growth chamber and greenhouse conditions often develops Ca deficiency. Since information on factors affecting Ca uptake and distribution in sorghum is limited, experiments were conducted to better understand factors associated with the enhancement of this disorder. Sorghum genotypes 'Redlan' and 'Martin' were grown in a growth chamber with 21.4 m*M* N (300 mg L^{-1}) at NO_3^-/NH_4^+ ratios of 300:0, 250:50, 200:100, and 150:150, with Ca levels of 1.25 or 2.50 m*M* (50 or 100 mg L^{-1}, respectively) to determine the effects of these N ratios on sorghum growth in nutrient solution and the occurrence of Ca deficiency. The same genotypes and conditions were used in a N source experiment where NO_3^-, NO_3^-/NH_4^+ (1:1), NH_4^+, and urea were compared. Symptoms of Ca deficiency were visible on young leaves of plants grown in solutions containing high proportions of NH_4^+ and low levels of Ca, but not with NO_3^- only or urea. The pH of solutions in the NO_3^-/NH_4^+ ratio experiment were higher with NO_3^- as the predominate N source. Growth and Ca concentrations decreased but total plant N concentrations increased with high proportions of NH_4^+ in the treatment solutions and with decreased Ca levels. Thus, N/Ca ratios increased progressively as the proportion of NH_4^+ in the nutrient solution increased, which also corresponded to increasing severity of Ca deficiency observed on leaves. Lower leaves had higher Ca concentrations than upper leaves indicating the relative immobility of Ca in sorghum. When comparing N sources, plants grown with NO_3^- or urea as the sole source of N generally had the best growth and the highest Ca concentrations, followed by plants grown with 1:1 NO_3^-/NH_4^+, and NH_4^+ only, respectively. Dry matter yields increased with increasing solution Ca levels regardless of N source. The enhanced uptake of Ca in sorghum when grown with only NO_3^- is believed to occur partially as a mechanism to counterbalance anion absorption and maintain proper cation/anion balance. It is likely that a reduction in Ca concentration in plants grown with high NH_4^+ was partially a result of reduced solution pH exerting antagonistic effects on Ca absorption or releasing Ca from cell wall anionic sites. Reduced and abnormal root growth resulting from high solution NH_4^+ may have enhanced the appearance of Ca deficiency symptoms by reducing Ca uptake due to reduced absorbing surface or lack of root tip growth.

Additional index words: Calcium uptake, Calcium accumulation, Ion balance, Mineral nutrition, Nutrient solution, *Sorghum bicolor* (L.) Moench.

SORGHUM grown under controlled conditions often develops Ca deficiency (R.B. Clark and J.W. Maranville, 1985, personal observations). Calcium deficiencies are common to many plants grown under conditions of controlled environments (Shear, 1975; 1979).

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These disorders are especially severe and frequently reported for tomato (*Lycopersicon esculentum* L.) blossom-end rot and lettuce (*Lactuca sativa* L.) tip burn. However, information on Ca deficiency disorders in sorghum grown in controlled environments is limited. The appearance of a *bull-whip* and leaf serration or curl disorder was reported for corn (*Zea mays* L.) and sorghum (*Sorghum vulgare* Pers.) grown under controlled conditions in nutrient solutions (Kawasaki and Moritsugu, 1979; Moritsugu and Kawasaki, 1985). The symptoms were induced only slightly by higher-than-normal levels of B^+, Mn^{++}, Cu^{++}, Zn^{++}, Mo^{++}, and Si^{++}, but were enhanced markedly by higher-than-normal levels of Mg^{++}, K^+, Na^+, NH_4^+, and P. However, P may not have been a direct cause of the disorder since P deficient leaves were also serrated. Similar symnptoms were induced by low levels of Ca and high temperatures. Calcium concentrations in newly developing leaves that became serrated were below 13 mmol kg^{-1} of dry matter. When sufficient Ca was added to treatment solutions that induced the disorder, the symptoms could be alleviated. From these results, the disorder that develops on corn and sorghum plants appears to be Ca deficiency or a disorder associated with Ca nutrition. The symptoms noted resembled Ca deficiency.

The functions of Ca in plant nutrition are not fully understood although many reviews have been written about Ca in recent years (Bangerth, 1979; Christiansen and Foy, 1979; Clark, 1984; Hanger, 1979; Hanson, 1984; Marme' 1983; Marschner, 1986; Shear, 1979; Smith, 1984). Calcium generally functions in cell wall and membrane stability or permeability (cell integrity), cell extension, enzyme modulation and metabolism, action potentials, phytohormones, and calmodulin. Even though Ca has been considered a macronutrient and accumulates in plants at relatively high concentrations, considerable evidence is available indicating that many Ca functions occur at very low Ca concentrations (Hanson, 1984; Marme', 1983; Smith, 1984).

Many factors affect Ca uptake and activity. Extensive interactions of other mineral elements with Ca have been reported (Clark, 1984; Hanson, 1984). The ions that strongly inhibit Ca uptake are H^+, K^+, Na^+, MG^{++}, Al^{+++}, and NH_4^+. The inhibitory role of NH_4^+ on Ca uptake is of special interest since NH_4^+ fertilization of plants is a common practice. Nutrient solutions containing some NH_4^+ become low in pH (near 4.0 or below) when sorghum and corn are grown in them (Bernardo et al., 1984; Clark, 1982). The uptake of cations at low pH (high H^+ concentration) is less than that at higher pH values, and Ca uptake is depressed more than the other cations (Kirkby, 1979; Marschner, 1986). Ammonium is absorbed more readily than is Ca and this can inhibit growth. Growth inhibition of sorghum by NH_4^+ was closely related to decreases in nutrient solution pH imposed by NH_4^+ uptake (Findenegg et al., 1982). Growth inhibition by NH_4^+ may be a result of Ca deficiencies that may occur under these conditions.

The physiological processes by which low pH or higher concentrations of other cations depress the uptake of Ca are not fully understood. The experiments reported here were conducted to study the effects of NH_4^+, different NO_3^-/NH_4^+ ratios, and different N sources in combination with two Ca levels on dry matter production of sorghum plants and Ca uptake, translocation, and accumulation in sorghum plants.

MATERIALS AND METHODS

The genotypes 'Redlan' and 'Martin' were used in these experiments since they have been observed to become Ca deficient when grown in nutrient solution. Seeds were germinated between rolled moist paper towels, and young seedlings were transferred to 0.3-strength nutrient solution for 5 d as previously outlined (Clark, 1982). Two uniform sized seedlings were transferred to 1.8-L glass containers painted black and held in place on supports by sponge rubber. In the first experiment, treatment solutions consisted of a total N concentration of 300 mg L^{-1} (21.5 m*M*) at NO_3^-/NH_4^+ ratios of 300:0, 250:50, 200:100, and 150:150 in combination with 50 or 100 mg L^{-1} of Ca (1.25 and 2.50 m*M*, respectively). Solutions were supplied with other nutrients as follows [micromolar (μM) element]: 7240 K, 1550 Mg, 1940 Cl, 1820 S, 65 P, 18 Mn, 50 B, 1.2 Zn, 1.2 Cu, 1.6 Mo, and 47 Fe as FeHEDTA (ferrichydroxyethyl-ethylenediaminetriacetate). The pH of solutions was adjusted initially to 5.4.

Plants were grown in a growth chamber with 16/8 h of light/dark at temperatures of 28/23 ± 1°C (light/dark). Relative humidity was maintained at 50 ± 5% and light intensity (photosynthetic photonflux density) was 410 μmol m^{-2} s^{-1} at plant level (1.0 m below the lamps). Containers were continuously aerated, and distilled water was added as needed to maintain solution level. The experimental design was a completely randomized factorial arrangement with four replications.

After 15 d of growth in treatment solutions, some plants showed Ca deficiency symptoms, and the experiment was terminated after plants had grown 21 d in treatment solutions. Plants were separated into roots, lower leaves (leaf nos. 1–5), and upper leaves (leaf nos. 6 and above), and the roots rinsed with distilled water. Leaves with deficiency symptoms were also separated from other plant parts. Plant parts were dried for 3 d at 70°C in a forced-air oven, weighed, and ground using a stainless steel mill to pass a 0.5-mm screen. Samples (100 mg) of ground material were pelleted and analyzed for Mg, P, Cl, K, Ca, S, Mn, Fe, Cu, and Zn by energy dispersive x-ray fluorscence (Knudsen et al., 1981). Homogeneous samples of the shoots and roots were analyzed for N concentrations using the Kjeldahl method.

A second, smaller experiment to monitor Ca distribution within individual leaves was conducted using only Martin plants. Solutions contained element concentrations the same as were described for the first experiment except only three NO_3^-/NH_4^+ ratios were used (250:50, 200:100, and 150:150) with 50 mg L^{-1} Ca. Plants grown in full-strength nutrient solution (Clark, 1982) served as the control treatment. The concentrations of Ca and N in the control solutions in micromolarity (μM) were 7540 Ca, 22 900 NO_3–N, and 2780 NH_4–N. The experiment was terminated after 21 d of growth in treatment solutions, and plants were separated into roots, lower leaves, and upper leaves. Each lower leaf was subdivided into two equal segments. The first segment (S1) was the leaf material from the point of attachment on the plant to the midsection of the leaf, and the second segment (S2) was the plant material from the midsection to the leaf tip. Each upper leaf was subdivided into three parts. The first part (P1) was the plant material from the point of attachment to one-fourth of the leaf length, the second part (P2) was the plant material from the end of the first part to three-fourths of the leaf length, and the third part (P3) was the remaining plant material to the leaf tip.

A third experiment was conducted to test N source on the expression of Ca deficiency in sorghum. The N compounds used in this experiment at 300 mg N L^{-1} were NO_3^- as Ca

and K salts, NH_4^+ and NO_3^- (1:1) as NH_4NO_3 salt, NH_4^+ as $(NH_4)_2SO_4$, and urea. Levels of Ca in solution were 50 or 100 mg L^{-1}, and other element concentrations were as described for the first experiment. At harvest, plants were water rinsed, blotted dry, and separated into roots, lower leaves, and upper leaves. Procedures and conditions for plant preparation and analysis were the same as those described for the first experiment.

RESULTS AND DISCUSSION

Symptoms of Ca deficiency were visible on young leaves of plants grown with solutions of high NH_4^+ and low Ca (Fig. 1). The symptoms appeared on the tips and margins of young leaves. Newly emerging leaves affected by Ca deficiency tended to curl toward the inside, became sticky, and later the edges were serrated. Marginal necrosis was highly developed on the upper part of young leaves and spread downward along the leaf with time. Root growth of Ca deficient plants was reduced and a decrease in root branching was noted. Root tips were dark brown and stubby compared to white, longer normal roots.

Plants grown with only NO_3 and urea appeared to grow normally with only minor tip-burn when Ca level in the treatment solution was low. Although considerable vegetative growth occurred, Ca deficiency symptoms were noted on plants grown with 150:150 NO_3^-/NH_4^+ solutions and the symptoms were more severe with only NH_4^+. Visual deficiency symptoms were consistent with low plant Ca concentrations. The association between visual symptoms and low Ca concentrations in plants indicated that the symptoms were most likely caused by a lack of Ca, and not from some other element.

The pH of the nutrient solutions increased with increasing NO_3 supply and decreased with increasing proportions of NH_4^+ similar to the results of Bernardo et al. (1984). With only NO_3 as a source of N in solutions, the pH increased from 5.4 to about 7.4 by the twelfth day. With a NO_3/NH_4^+ ratio of 150:150, the

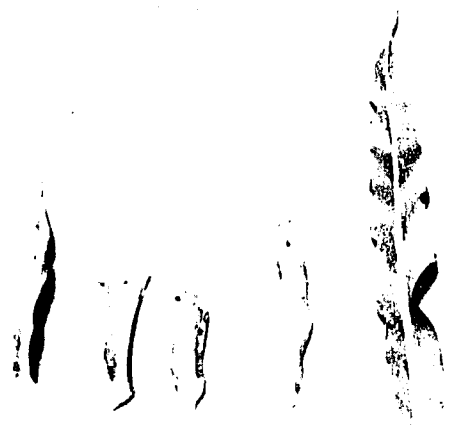

Fig. 1. Calcium deficiency symptoms of sorghum leaves from plants grown with high levels of NH_4, and a healthy single leaf (right) from a plant grown with only NO_3.

pH declined from an initial 5.4 to 3.8 within 14 d. The capability of plants to change the pH of the nutrient solution appeared to be due to the unequal absorption of cations and anions (Kirkby, 1979; Kirkby and Mengel, 1967; Marschner, 1986). High pH values with higher NO_3 in solution have been attributed to excretion of hydroxyl or bicarbonate ions, or both, from the roots to solutions, and increased organic acid synthesis to balance charges after NO_3^- reduction (Kirkby and Mengel, 1967). Plants grown with high proportions of NH_4^+ in solution tended to expell H^+ to balance the positive charges of NH_4^+ taken up.

As the ratio of NO_3/NH_4^+ in the nutrient solutions increased, dry matter yields of both genotypes increased at either level of Ca (Table 1). The increase in dry matter yield for Redlan plants was slightly greater at the higher than at the lower Ca level. Both genotypes produced more dry matter when grown with the higher

Table 1. Calcium concentrations in roots (R), lower leaves (LL), upper leaves (UL), deficient leaves (DL), and the whole plant (WP), and dry matter yields, N concentrations, and N/Ca ratios of Redlan and Martin plants grown at different Ca levels and NO_3/NH_4^+ ratios.

Genotype	Ca level	NO_3/NH_4^+ ratio (300 mg pot^{-1})	Ca in plant parts R	LL	UL	DL	WP	Dry matter yield	N conc.	N/Ca ratios
	mg L^{-1}				mg g^{-1}			g plant^{-1}	mg g^{-1}	
Redlan	50	300:0	1.63	2.32	0.70	--‡	1.67	3.35	22.9	13.7
		250:50	0.97	2.31	0.64	1.23	1.41	3.09	26.9	19.0
		200:100	0.66	2.07	0.64	1.55	1.27	2.70	27.2	21.4
		150:150	0.66	1.96	0.42	0.73	1.11	2.55	25.3	22.8
	100	300:0	2.68	3.13	0.70	--	2.64	4.86	21.1	8.0
		250:50	1.56	3.18	0.67	3.05	2.14	3.80	25.1	11.7
		200:100	1.17	2.78	0.64	2.52	1.19	3.33	30.3	25.5
		150:150	1.41	1.79	0.42	1.58	1.54	3.33	24.1	15.6
Martin	50	300:0	1.46	3.01	0.76	--	2.05	2.84	21.9	10.7
		250:50	0.99	2.77	0.83	1.77	1.71	2.82	25.3	14.8
		200:100	0.86	2.07	0.57	2.01	1.39	2.35	29.3	21.1
		150:150	0.69	1.65	0.52	1.67	1.14	2.13	25.5	22.3
	100	300:0	1.82	4.23	1.44	--	2.83	3.90	23.7	8.3
		250:50	1.82	3.47	0.92	2.68	2.77	3.70	27.0	9.7
		200:100	1.40	4.15	0.91	2.54	2.27	3.45	33.9	14.9
		150:150	0.94	2.35	0.55	1.63	1.51	3.39	24.4	16.2
LSD†			0.57	0.74	0.33	1.36	0.43	0.98	4.0	1.2

† LSD at $P = 0.05$ for differences among means in columns for a particular variable.
‡ No Ca deficiency noted in any leaves so DL were not separated.

Table 2. Calcium concentrations in roots (R), lower leaves (LL), upper leaves (UL), whole plant (WP), and dry matter yields, N concentrations, and N/Ca ratio of Redlan and Martin plants grown in different Ca levels and N sources.

Genotype	Ca level	N source	Ca in plant parts R	LL	UL	WP	Dry matter	N conc.	N/Ca ratio
			mg g^{-1}				g plant^{-1}	mg g^{-1}	
Redlan	50	NH_4^+	1.22	1.08	0.13	0.87	0.82	24.0	27.6
		NO_3^-	1.83	3.30	2.99	2.56	3.32	13.6	5.3
		NH_4^+/NO_3^-	1.05	1.53	0.71	1.16	2.17	22.9	19.6
		Urea	1.16	2.20	0.80	1.58	3.34	29.3	18.5
	100	NH_4^+	1.53	1.11	0.30	1.01	1.04	21.0	20.8
		NO_3^-	2.42	4.75	2.83	3.44	3.58	13.6	3.9
		NH_4^+/NO_3^-	1.37	1.84	1.07	1.52	2.27	23.3	15.3
		Urea	5.60	5.04	2.72	4.93	3.42	35.4	7.2
Martin	50	NH_4^+	0.85	1.17	0.08	0.88	0.89	29.3	33.4
		NO_3^-	1.81	2.52	2.53	2.18	3.28	14.5	6.7
		NH_4^+/NO_3^-	0.87	1.53	0.75	1.08	2.46	26.7	24.7
		Urea	0.83	1.67	1.33	1.31	3.10	22.6	17.3
	100	NH_4^+	1.11	1.90	0.48	1.40	0.98	27.1	19.4
		NO_3^-	2.20	4.74	3.60	3.42	3.45	14.8	4.3
		NH_4^+/NO_3^-	1.16	2.35	1.03	1.60	2.95	25.4	15.9
		Urea	1.08	2.86	1.20	1.94	3.30	24.3	12.3
LSD†			1.87	1.10	1.13	1.23	0.59	4.4	6.6

† LSD at $P = 0.05$ for differences among means in columns for a particular variable.

level of Ca in solution under all NO_3^-/NH_4^+ ratios compared to low Ca. The positive association between growth and higher Ca level in the solutions indicated the essentiality of adequate Ca for normal sorghum growth.

The highest dry matter yield was produced by plants grown with NO_3^- and urea solutions (Table 2). Plants grown with NO_3^-/NH_4^+ (1:1) ranked third in dry matter yield, while those grown with only NH_4^+ were lowest. The satisfactory growth of sorghum plants using urea as a sole N source in nutrient solution has been consistently observed in other of our experiments (Solomon, 1984). Urea enzymatically decomposes into CO_2 and NH_4^+ in soil (Ladd and Jackson, 1982). In nutrient solution, however, it is quite likely that the molecule is taken up intact and metabolized internally either in the root or aerial portion (Harper, 1984). Urea might be expected to act more like NO_3^- than NH_4^+ in this case. Both genotypes responded similarly to N source with regard to dry matter production.

Regardless of the N source, dry matter yield increased with increasing Ca levels in the nutrient solutions. Both genotypes had similar patterns of dry matter production in response to Ca level or N source. The consistent response of NO_3^- over NH_4^+ in producing healthy growth of sorghum has also been observed in wheat (*Triticum aestivum* L.) (Cox and Reisenauer, 1973).

As the NO_3^-/NH_4^+ ratio increased, Ca concentration in the whole plant tissue increased (Table 1). In solutions with NO_3^- only, Ca concentration in roots was higher than that in roots of plants grown with other N treatment combinations for both genotypes. Higher Ca concentrations were also found in shoots of plants grown at the higher NO_3^-/NH_4^+ ratios. Higher Ca concentrations in plants grown with higher proportions of NO_3^- may have resulted from enhanced Ca uptake in response to high NO_3^- absorption. Plants grown with NO_3^- have greater cation uptake, including Ca, than plants grown with lower proportions of NO_3^- (Kirkby, 1979; Kirkby and Mengel, 1967). The stimulatory effect of NO_3^- on Ca uptake agrees with the results of other research (Cox and Reisenauer, 1973). The restriction of new root growth due to higher NH_4^+ in solution and subsequently lower pH values also resulted in reduced Ca uptake. This probably occurred, in part, because Ca, which moves across the root apoplastically (Hanson, 1984), was restricted due to the lack of root tip growth. Similar results have been noted for other grass plants (O'Brien and Carr, 1970). Older parts of roots have endodermal suberization that would block apoplastic movement of Ca across roots (Hanson, 1984). Explanations for the depressing effects of NH_4^+ on Ca uptake have been attributed to carrier competition among cations for the same absorption sites (Epstein, 1972), decreased membrane stability and hydrophobicity which would enhance greater uptake of the other cations compared to Ca (Hanson, 1984), and the reduced ability of Ca to compete against other more quickly absorbed cations, especially NH_4^+, for anion equivalents to neutralize positive charges (Kirkby, 1979).

Increasing Ca levels in solutions resulted in higher Ca concentration in plant parts or the whole plant at each N regime. Lower leaves of both genotypes retained higher concentrations of Ca compared to upper leaves of plants grown at each Ca level and N regime (Tables 1 and 2). This pattern of Ca distribution and the appearance of Ca deficiency symptoms only on young leaves indicated a low Ca mobility in sorghum.

The segment of lower leaf nearest the stalk had lower Ca concentrations than the segment away from the point of attachment (Table 3). Calcium concentrations in each segment and in the whole plant increased gradually with increased NO_3^- in the nutrient solution.

Calcium concentration in each upper leaf also increased from the base to the tip. Although the concentration of Ca in the leaf tip was greater than that in other leaf sections, Ca deficiency symptoms appeared most predominately at the leaf tip. Perhaps,

physiologically active Ca in the tips of upper leaves was insufficient to allow normal growth. Calcium may have been inactivated by other elements like P (Moritsugu and Kawasaki, 1985) or by malate or oxalate (Hanson, 1984; Van Egmont, 1979). Tips of leaves from control plants had higher Ca concentrations compared to plants from other N treatments (Table 3), and this amount of Ca appeared sufficient to meet plant needs. Higher Ca concentrations in the leaf tips in these experiments generally agreed with the results of other researchers (Moritsugu and Kawasaki, 1985; O'Brien and Carr, 1970) where high Ca concentrations were found in tips of corn leaves. Apparently, the formation of suberin lamellae on parenchyma cells forming a sheath around the vascular tissues could have restricted apoplastic movement of Ca. This would result in high amounts of Ca being moved to the tips with less transferred laterally.

Nitrogen concentrations in the plants were higher in both genotypes when the NO_3^-/NH_4^+ ratio was 200:100 at either level of Ca (Table 1). Lowest N concentrations were noted in plants supplied with only NO_3^-. This probably occurred because of a dilution effect from the higher dry matter production when plants were grown with high amounts of NO_3^- solution.

The N/Ca ratio increased progressively in plants as the proportion of NH_4^+ in the nutrient solution increased or the nutrient solution Ca level was reduced, or both (Table 1). A strong association between Ca deficiency symptoms and higher proportions of NH_4^+ in the solutions was noted so that high N/Ca values were also associated with severity of Ca deficiency. The N/Ca ratio appeared to be related to Ca disorders in other plants (Shear, 1975). Therefore, N/Ca ratios might be used as a trait to evaluate plants for Ca nutrition.

The results of the N source experiment showed that sorghum plants grown in NO_3^- solutions had the lowest N concentration compared to the other N sources (Table 2). Plants grown with NO_3^- produced high dry matter yields, which may have resulted in N dilution. However, urea grown plants also produced high dry matter without reduced plant N concentrations, which would result in total N content of these plants being markedly higher than that of those grown with the other sources. Urea appeared to be a good source of N for solutions when growing sorghum to maximize productivity and eliminate Ca deficiency symptoms that often occur. Nitrogen concentrations of plants grown at the high Ca level with NO_3^- as the sole source of N were similar to those for plants grown with low Ca, even though plants grown at the high Ca level generally produced more dry matter. The effects of the other N sources on N concentration in plants were not consistent across solution Ca levels or genotypes. Significant ($P \leq 0.05$) N source × Ca level and N source × genotype interactions occurred. For example, Redlan plants grown with only NH_4^+ and 50 mg Ca L^{-1} ranked next to the highest for N concentration, but at the high Ca level, Redlan plants grown with only NH_4^+ ranked next to the lowest. Martin plants grown with 50 or 100 mg Ca L^{-1} and with NH_4^+ consistently had the highest N concentrations (Table 2).

The source of N and the Ca level in the nutrient solution had marked effects on N/Ca ratios. An apparent association between higher dry matter yield and lower N/Ca value was observed. For example, Redlan plants grown in 50 mg Ca L^{-1} solutions with N sources of NO_3^-, urea, 1:1 NO_3^-/NH_4^+, and NH_4^+ had N/Ca values of 0.53, 1.85, 1.96, and 2.76, respectively. Reduction in dry matter yield and severity of Ca disorders were associated with these progressively higher N/Ca values, and higher proportions of NH_4^+ in solution.

Table 3. Calcium concentrations in roots (R), first segment of lower leaves (S1), second segment of lower leaves (S2), first part of upper leaves (P1), second part of upper leaves (P2), third part of upper leaves (P3), and the whole plant (WP) of Martin plants grown at different NO_3^-/NH_4^+ ratios and control treatment.

NO_3^-/NH_4^+ ratio	Ca in plant parts						
	R	S1	S2	P1	P2	P3	WP
	mg g^{-1}						
Control	7.35	8.43	12.06	2.83	3.52	5.97	7.40
250:50	2.70	2.25	3.23	1.56	2.48	4.18	2.61
100:100	3.01	1.51	2.18	1.03	1.41	3.27	2.24
150:150	1.16	0.93	1.58	0.63	0.89	2.16	1.12
LSD†	3.89	1.59	1.60	1.25	1.52	1.70	2.15

† LSD 0.05 for differences among means in columns for a particular variable.

REFERENCES

Bangerth, F. 1979. Calcium-related physiological disorders of Plants. Annu. Rev. Phytopathol. 17:97–122.

Bernardo, L.M., R.B. Clark, and J.W. Maranville. 1984. Nitrate/ammonium ratio effects on nutrient solution pH, dry matter yield, and nitrogen uptake of sorghum. J. Plant Nutr. 7:1389–1400.

Christiansen, M.N., and C.D. Foy. 1979. Fate and function of calcium in tissues. Commun. Soil Sci. Plant Anal. 10:427–442.

Clark, R.B. 1982. Nutrient solution growth of sorghum and corn in mineral nutrition studies. J. Plant Nutr. 5:1039–1057.

———. 1984. Physiological aspects of calcium, magnesium, and molybdenum deficiencies in plants. p. 99–170. *In* F. Adams (ed.) Soil acidity and liming. 2nd ed. ASA, CSSA, SSSA, Madison, WI.

Cox, W.J., and H.M. Reisenauer. 1973. Growth and ion uptake by wheat supplied nitrogen as nitrate, or ammonium or both. Plant Soil 38:363–380.

Epstein, E. 1972. Nutrient elements in physiological processes. p. 305–308. *In* E. Epstein (ed.) Mineral nutrition of plants: Principles and perspectives. John Wiley & Sons, Inc., New York.

Findenegg, G.R., M. Salihu, and N.A. Ali. 1982. Internal self-regulation of H^+-ion concentration in acid damaged and healthy plants of *Sorghum bicolor* (L.) Moench. p. 174–179. *In* A. Scaife (ed.) Proc. 9th Int. Plant Nutr. Colloq., Warwick, England. Commonwealth Agricultural Bureaux, Farnham Royal, Buckshire, England.

Hanger, B.C. 1979. The movement of calcium in plants. Commun. Soil Sci. Plant Anal. 10:171–193.

Hanson, J.B. 1984. The functions of calcium in plant nutrition. p. 149–208. *In* P.K. Tinken and A. Lauchli (ed.) Advances in plant nutrition. Praeger, New York.

Harper, J.E. 1984. Uptake of organic nitrogen forms by roots and leaves. p. 165–170. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, SSSA, Madison, WI.

Kawasaki, T., and M. Moritsugu. 1979. A characteristic symptom of calcium deficiency in maize and sorghum. Commun. Soil Sci. Plant Anal. 10:41–56.

Kirkby, E.A. 1979. Maximizing calcium uptake by plants. Commun. Soil Sci. Plant Anal. 10:89–113.

———, and K. Mengel. 1967. Ionic balance in different tissues of tomato plant in relation to nitrate, urea, or ammonium nitrate. Plant Physiol 42:6–14.

Knudsen, D., R Clark, J.L. Denning, and P.A. Pier. 1981. Plant analysis of trace elements by x-ray. J. Plant Nutr. 3:61–75.

Ladd, J.N., and R.B. Jackson. 1982. Biochemistry of ammonification. *In* F.J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22:173–228.

Marme', D. 1983. Calcium transport and function. p. 599–625. *In* A. Lauchli and R.L. Bieleski (ed.) Inorganic plant nutrition. Encyclopedia of plant physiology, new series. Vol. 15B. Springer-Verlag, New York.