Published September, 1976

Effect of Rice Straw Incorporation on Rice Plant Growth and Nutrition[1]

D. Niranjan Rao and D. S. Mikkelsen[2]

ABSTRACT

Rice (*Oryza sativa* L.) straw disposal by soil incorporation may have adverse effects on subsequent rice seedling growth from toxic anaerobic decomposition products and temporary immobilization of the soil mineral N. Glasshouse and laboratory studies were conducted to study the problem under conditions of direct sowing of rice.

Samples of a typical rice soil, Sacramento clay, which is a very fine, montmorillonitic thermic Vertic Hapiquall, were collected. Rice straw in amounts of 0, 0.25, and 0.5% was added to soils which were incubated aerobically for 0, 15, and 30 days in a glasshouse plant growth experiment, and for 0 and 20 days in preparation for a laboratory soil incubation experiment. Nitrogen was applied at the rate of 50 ppm in the glasshouse experiment and 50, 75, and 100 ppm in the laboratory study. N was added after aerobic incubation and subsequently rice was grown for 21 days to measure seeding growth effects. The glasshouse experiment with rice cultivar 'Earlirose' also evaluated the production of acetic, propionic, and butyric acids, while the laboratory soil incubation experiment was for N transformation data.

The results clearly indicate that when soil and rice straw were not incubated prior to planting rice seedlings, applied N was immobilized, causing inhibition of plant growth and low N content of plants. When rice straw was incubated in soil for 15 to 30 days before planting seedlings, N immobilization was reduced and plant growth was promoted. Nitrogen immobilization was observed to be the principal cause of inhibition of plant growth from added rice straw. Organic acids (acetic and propionic) were produced in amounts considered to be below the toxic concentration of plants. Butyric acid was not found in the soil extracts.

Additional index words: Organic acids, N immobilization, Straw incubation, *Oryza sativa.*

RICE (*Oryza sativa* L.) straw incorporated into a flooded soil may exert a twofold effect on rice plant growth. First, the added straw as a substrate for microorganisms may produce anaerobic decomposition products, most importantly organic acids, which affect plant growth. The second effect occurs during mineralization of straw (C/N 40-50:1) when microorganisms temporarily immobilize part of the soil mineral N into organic forms which are not immediately available to rice plants.

The kind, amount, and rate of organic acid production in flooded soils depend largely on the nature of the organic materials added. Yamane and Sato (18) observed that organic acid production was rapid and in large amounts with added glucose, less with starch, and was suppressed by cellulose and gelatin. The principal organic acids produced were acetic and butyric acids which respectively produced amounts of 9.7 and 3.0 meq/100 g soil with glucose, 7.5 and 1.9 with starch, 5.0 and 1.0 with cellulose, and 2.8 and < 1.0 with gelatin.

Green manure crops and rice straw are commonly added to flooded soils where rice is grown. Green manure crops decompose faster than rice straw in flooded soils according to Sicar and Bhowrick (12) and both may produce organic acids. Chandrasekaran and Yoshida (4) incorporated fresh leaves of *Sesbania* sp. and observed under anaerobic conditions the production of acetic, propionic, butyric, and isobutyric acids. The peak organic acid production occurred 5 days after application with acetic acid produced in amounts of 2.93 meq/100 g soil, propionic 0.41 meq, butyric 0.28 meq, and isobutyric 0.12 meq. Gotoh and Onikura (6, 7), in studies of rice straw decomposition, found acetic acid production in significantly higher amounts than butyric acid and only trace amounts of other acids. Peak production of acetic acid occurred about 10 to 14 days after application with rice straw, and within 7 days with easily decomposable organic materials. The concentration of acetic acid in the soil solution with 1.0% of rice straw added was 14×10^{-3} *N*.

The toxicity of organic acids to rice plants depends on what types are present. Extensive studies (13, 14, 16) show that among the monobasic aliphatic acids their inhibitory effects increase with increasing molecular weight. Inhibition of rice plant growth by the acids studied was in the order of butyric > propionic > formic.

After studies with several organic acids in solution culture, Takijima (15) suggested that toxic concentrations (25% reduction of root length) of various acids were in the magnitude of formic, 3.32 mN; acetic 4.6 m*N*; butyric, 0.7 m*N*. Chandrasekaran and Yoshida (4) added 0.5 to 1.0 mmole of organic acids (formic, acetic, propionic, and butyric) per 100 g soil and transplanted 14-day-old rice seedlings. Even at 0.5 mmole/100 g soil, the organic acids reduced plant dry weights.

Straw mineralization and N immobilization in soil are closely related, since most of the N (approximately 98%) is in the organic fraction, with only 2 to 3% in the inorganic forms. The addition of high-carbon and low-N crop residues immobilizes soil N and/or applied N. Since the soil microbial population is

[1] Contribution from the Dep. of Agronomy and Range Science, Univ. of California, Davis, CA 95616. Received 27 Sept. 1975.

[2] Former graduate student, now research scientist, IRI Research Inst., Inc. New York, N.Y., and professor of agronomy.

much more efficient than the crop in utilizing available soil N, crop plants are often deprived of an adequate supply (2).

Rai (10) studied the effect of incorporating sorghum (*Sorghum bicolor* L.) straw on the yield of a subsequent sesame (*Sesamum indicum*) crop. When N was not applied, incorporation of the straw 30 days before planting depressed sesame yields. When the straw was either burned or removed from the field, yields were increased. With N application (48 kg/ha or more) sesame yields were the same with any of the three methods of straw disposal. Rai suggested that N immobilization was the reason for the yield reductions when straw was incorporated without N application. Krantz et al. (8) had similar results with sugarbeet (*Beta vulgaris*) and safflower (*Carthamus tinctorius*). Adding N fertilizer together with the straw residues generally reduced the uptake of fertilizer N by succeeding crops. The reduced uptake was a consequence of microbial N immobilization.

Williams et al. (17) studied the relation of rice grain yields to the C:N ratios of incorporated rice straw. They altered the N content of the straw by adding vetch (3.87% N). Their results indicate that the critical N content of the rice straw was 0.54%. Straw with a nitrogen value above 0.54% increased rice yields while straw-N below 0.54% reduced yields.

When crop residues high in N content are incorporated, mineralization of N will occur which ultimately results in higher crop yields. This is especially true with incorporation of leguminous green manure crops.

Another way of minimizing the immobilization of applied N to crop plants is to allow sufficient time for the crop residue to decompose before planting the crop. Ferguson and Gorby (5) incorporated straw in the soil in early fall and applied N in the following spring before planting oats (*Avena sativa* L.) and wheat (*Triticum aestivum*). No N deficiency or yield reduction resulted from the straw addition. Chaminade (3), after incubating ground wheat straw for 0.5, 2, 4, and 6 months, found that straw lost its depressing effects in 2 months and that yields were higher in the presence of straw decomposed for longer incubation periods than in controls.

The present studies were initiated to observe the effects of organic acid production and N immobilization on the growth of rice. The straw additions at rates of 0.25 and 0.50% correspond to field straw application rates of 5.6 and 11.2 tons/ha, respectively.

MATERIALS AND METHODS

Sacramento clay soil, pH 6.7 (1:5 ratio), which is a very fine, montmorillonitic thermic Vertic Hapiquall, was collected from the surface 30 cm of a field that had previously been cropped with rice. The soil contained 50.6% clay, 47.6% silt, and 1.8% sand. Total C content was 1.164%; total N, 0.079%; and the soil C:N ratio was 15. The soil was dried, screened, and 5-kg lots were weighed into 8-liter glazed pots. Mature rice straw, containing 36.3% C and 0.75% N (C:N ratio 48:1) was added to appropriate pots, in four replications, to provide rates of 0, 0.25, and 0.50% of soil weight. These pots were subsequently incubated at 21 C for 0, 15, and 30 days at field capacity (67% moisture). After the appropriate incubation periods, all pots were fertilized to receive 50 ppm N as $(NH_4)_2SO_4$, 25 ppm P, and 31 ppm K as KH_2PO_4. After thorough fertilizer incorporation, five 15-day-old rice seedlings (*Oryza sativa* 'Earlirose') selected for uniformity were transplanted into each pot. These pots were kept flooded with distilled water at a depth of 3 to 4 cm for the balance of the experiment.

Soil cores for organic acid analyses were taken with 20 mm diam glass tubes at weekly intervals in the incubated pots. The wet soil was weighed (300 g wet wt) into 125 ml Erlenmeyer flasks with 50 ml deionized-distilled water, to which 15 ml of 1:1 H_3PO_4 was added to bring the pH to 1.0. The flasks were shaken for 30 min on a reciprocating shaker, then filtered through Buchner filters, allowing collection of all the filtrate. The moisture in the soil samples was determined by drying duplicate sets of samples. The filtrate was analyzed for acetic, propionic, and butyric acid with a Varian gas chromatograph, model 1800, equipped with a hydrogen flame detector, by a method described by Laskowski and Broadbent (9). The organic acids were separated on a 1.51 m by 0.32-cm -o.d.glass column packed with 6% FFAP on 80/100 porapak Q. The carrier gas was N, with rate of flow regulated at 30 ml/min. Air flow was 200 ml/min, and hydrogen flow was maintained at 25 ml/min. The column was maintained at 180 C isothermal, the column inlet at 230 C, and the detector at 260 C. The amount of sample injected was 5 μl. The peak area was measured with a Varian electronic integrator, model 477, with digital printout. The recorder responses were calibrated by comparing peak areas of the unknown with those of known quantities of organic acids.

The plants were grown for 21 days in a glasshouse, where the day temperature was 37.8 C and the night was 23.9 C, with a day-length of 13 hours. At the end of the experiment the plant height was measured before plants were harvested and separated into sheath and leaves. These plant parts were oven-dried at 75 C for 48 hours, and the dry weight yields recorded. The plant parts were analyzed for N, P, and K.

The second experiment was a laboratory soil incubation study in which 20 g of soil, with 100 ml of distilled water, was incubated in 250-ml Erlenmeyer flasks with 0, 0.25, and 0.50% ground rice straw incubated for 0 and 20 days at 25 C, with 0, 50, 75, and 100 ppm of applied N. The incubated treatments, maintained at field capacity for 20 days, were flooded with 100 ml distilled water. Prior to flooding, 50 ppm N was added to selected treatments already incubated with 0, 0.25, and 0.50% of rice straw. At the end of the flooded incubation period soil samples were extracted with 2*N* KCl to separate the mineral N by the method described by Bremner (2). The soil was then dried and ground to estimate the organic N (1).

RESULTS

Plant Height

The data on plant height and associated statistical analysis are presented in Table 1. Plant height with no pre-planting incubation was 71.3 cm without rice straw added, 51.5 cm with 0.25% rice straw, and 33.3 cm with 0.5% rice straw. When soil was incubated with 0.25% straw for 15 days, and 0.25% and 0.5% straw for 30 days, plant height was significantly increased compared with no rice straw at the same incubation period.

Plant Weights

The leaf and sheath dry weights are presented in Table 1. Dry matter reductions due to straw additions and the beneficial effects of incubations are demonstrated. Leaf dry weight with no incubation was 409 mg/plant with no straw, 160 mg with 0.25% straw, and 71 mg with 0.5% straw.

With soil incubation, straw additions gave increased leaf dry matter yield except for the 0.5% straw level and 15 days of incubation. The effect of rice straw and incubations on sheath dry weights were the same as for leaf dry weights.

Nutrient Uptake

The plant (leaves and sheaths) were analyzed for N, P, and K. Nitrogen was the element affected most (Table 2). Without incubation, straw additions re-

Table 1. Effect of added rice straw on the growth and dry weight of rice seedlings.

Treatment				
No. of days incubated	Amounts of straw added	Plant height	Leaf dry wt	Sheath dry wt
	%	cm	mg	
0	0	71.3 a	408.7 a	392.7 a
0	0.25	51.5 d	159.5 e	185.8 e
0	0.50	33.3 e	71.3 f	88.0 f
15	0	69.9 ab	358.1 abc	337.7 abc
15	0.25	70.0 ab	370.6 ab	370.5 ab
15	0.50	63.2 c	255.1 d	264.9 d
30	0	66.2 bc	303.0 cd	295.0 cd
30	0.25	68.7 ab	323.6 bc	310.2 bcd
30	0.50	71.4 a	391.1 a	395.5 a
Analysis of variance: F values				
Days of incubation		**	**	**
Amount of straw		**	**	**
Interaction		**	**	**
C.V., %		4.5	1.8	15.9

** Significance at 1% level of confidence.

Table 2. Effect of added rice straw on the nutrient composition of rice plant parts.

Treatments							
No. of days incubated	Amounts of straw added	Leaf			Sheath		
		N	P	K	N	P	K
	%	%					
0	0	3.73	0.37	2.37	2.26	0.46	2.95
0	0.25	3.41	0.35	2.02	1.29	0.42	2.66
0	0.50	1.89	0.28	1.65	1.15	0.35	1.87
15	0	3.38	0.40	2.23	1.72	0.47	3.82
15	0.25	3.19	0.37	2.11	1.72	0.45	2.59
15	0.50	2.87	0.36	2.19	1.83	0.43	2.49
30	0	3.51	0.44	1.83	1.79	0.46	3.16
30	0.25	3.34	0.41	2.12	2.05	0.48	3.12
30	0.50	3.12	0.37	1.79	1.84	0.45	2.34

Table 3. Effect of rates of straw addition and days of incubation on organic acid production.

Treatment		Amount of organic acid produced†			
		Acetic acid			Propionic acid
No. of days incubated	Amounts of straw added	7th day	14th day	21st day	21st day
	%	μeq/20 g soil			
0	0	2.15	-	-	-
0	0.25	2.30	-	-	-
0	0.50	2.62	26.53	7.13	7.64
15	0	2.45	-	-	-
15	0.25	0.59	-	-	-
15	0.50	0.05	2.00	-	-
30	0	1.27	-	-	-
30	0.25	1.80	-	-	-
30	0.50	0.05	0.11	-	-

† No butyric acid was detected.

duced the N content of plant parts to half that of the control (leaf N at 0, 0.25, and 0.5% straw was respectively 3.73, 3.41, and 1.89%). Incubation reduced the differences between zero straw and other straw rates, with the differences declining with length of incubation. Phosphorus and K concentrations were affected only slightly, being reduced without incubation, and increasing progressively (but slightly) with time of incubation.

Organic Acid Production

Concentrations of organic acids present in the soils sampled at 7-day intervals are shown in Table 3. The production of organic acid was very small on the 7th day ranging between 0.05 and 2.62 meq/20 g soil. When 0.5% rice straw was added without incubation, 26.53 meq of acetic acid per 20 g soil and 7.64 meq of propionic acid per 20 g soil were produced on the 14th and 21st days, respectively. Butyric acid was not detected in the extracted soil solutions.

Immobilization of Nitrogen

Table 4 shows the amounts of N immobilized, the change in organic N content, and the recovery of applied N in the laboratory soil incubation study.

Without pre-flood incubation and added straw, applied N increased the N content of the organic and inorganic fractions. At the 0 rice straw rate, 50, 75, and 100 ppm added N respectively, resulted in 33.0, 49.5, and 66.0 ppm N, immobilized into the organic fraction and an increase of 13.2, 28.6, and 48.0 ppm N in the inorganic N fraction. With 0.25% straw added, 50, 75, and 100 ppm added N resulted in 60.5, 77.0, and 77.0 ppm N immobilized, with no consistent increase in the inorganic N fraction. The highest rice straw rate (0.5%) gave N immobilization similar to that for 0.25% straw.

When soil was pre-flood incubated for 20 days, adding N along with rice straw at the beginning of the incubation period immobilized more N than did adding N after incubation. Adding 50 ppm N at the beginning of the incubation period immobilized 87.8, 38.5, and 77.0 ppm N with 0, 0.25, and 0.5% straw

Table 4. Effect of added rice straw, number of days of incubation, and added N on immobilization of applied N.

Incubation time	Amount of straw added	Amount of N applied	Amount of N immobilized	Change in inorganic N	Added N recovered
Days	%	ppm			
0	0	0	0	0	0
0	0	50	33.0	13.2	46.2
0	0	75	49.5	28.6	78.1
0	0	100	66.0	48.0	114.0
0	0.25	0	0	0	0
0	0.25	50	60.5	(2.2)‡	58.3
0	0.25	75	77.0	4.4	81.4
0	0.25	100	77.0	(2.2)‡	74.8
0	0.50	0	0	0	0
0	0.50	50	82.5	0	82.5
0	0.50	75	99.0	(4.4)‡	94.6
0	0.50	100	115.5	0	115.5
20	0	0	0	0	0
20	0	50	87.8	46.2	134.0
20†	0	50	38.5	70.4	108.9
20	0.25	0	0	0	0
20	0.25	50	38.5	0	38.5
20†	0.25	50	27.5	17.6	45.1
20	0.50	0	0	0	0
20	0.50	50	77.0	4.4	81.4
20†	0.50	50	60.5	39.6	100.1

† Nitrogen applied after incubation, at time of flooding. ‡ ( ) Net loss of nitrogen.

additions, respectively. Adding N after 20 days of pre-floid incubation immobilized 38.5, 27.5, and 60.5 ppm N with 0, 0.25, and 0.5% straw additions, respectively. The inorganic N fraction with the addition of N after incubation also increased by 24.2, 17.6, and 35.2 ppm at 0, 0.25, and 0.5% rice straw, respectively over corresponding treatments which received N at the time of pre-flood incubation.

DISCUSSION

Rice plant growth, as represented by plant height and leaf and sheath dry weights, was inhibited by rice straw added at the time of planting. The decrease in plant growth with increasing straw rates was highly significant, e.g., 71.3 cm of height at 0% straw, 51.5 cm at 0.25%, and 33.3 cm at 0.5%. Incubating the straw for 15 to 30 days, before planting considerably reduced its inhibitive effects, and improved plant growth over the controls except that 0.5% rice straw appeared to be too heavy a straw load to be offset by 15 days of incubation.

The rice plants grown on soil with incorporated rice straw did not show symptoms of organic acid toxicity as described by Rao and Mikkelsen (11). The only distinct symptom observed was N deficiency in pots which were not incubated. These symptoms were not seen in treatments incubated for 15 and 30 days.

Chemical analyses show that the N content of leaves and sheaths decreased with decreased plant growth, and to a greater degree with no incubation treatments. It is apparent that rice straw added without incubation induced N deficiency. The laboratory results support this argument. When soil and rice straw was not incubated, added N was transformed into organic N forms, unavailable to the rice plants, with deficiency resulting. Gotoh and Onikura (7) also observed N deficiency at early stages of rice plant development when rice straw was incorporated at rates up to 16.8 tons/ha (9.75%).

When rice straw was incubated for 15 to 30 days before planting the rice seedlings did not develop N-deficiency symptoms. Similarly, a 20-day soil incubation in the laboratory study did not greatly decrease inorganic N (available to plants) even though organic N was greater than in control soils. When N was added after incubation, however, the amount of inorganic N was the highest, so there was a definite beneficial effect from incubating the rice straw for 15 to 30 days. Incubating the soil at field capacity promoted aerobic decomposition, thus mineralizing considerable substrate carbon. The reduction in mineralizable C at the time of the N addition limited the nitrogen incorporated into microbial tissue. For this reason, when N additions were withheld until pre-flood incubation was over, they did not produce N-deficiency symptoms in plants even at 0.5% levels of rice straw addition. Ferguson and Gorby (5) similarly reduced N immobilization by incorporating crop residue in the fall and applying N in the following spring for a wheat crop.

Rice straw additions did not produce significant amounts of acetic, propionic, or butyric acids, which would be toxic to rice plants. Further, the plants showed no symptoms of organic acid toxicity.

These results show that the principal adverse effect of rice straw incorporation, under the present experimental conditions, was immobilization of N caused by decomposition of straw of a wide C:N ratio. Incubation of rice straw in soil for 15 to 30 days reduced the level of N immobilization and enhanced plant growth. Applying fertilizer N at the onset of rice straw decomposition resulted in a greater degree of nitrogen immobilization than applications made after incubation. The amount of organic acids produced, mainly acetic and propionic, was below the toxic concentration of rice seedlings.

LITERATURE CITED

1. Assoc. of Official Agric. Chemists (A.O.A.C.). 1960. Official methods of analysis. 9th Ed. 2-037.
2. Bremner, J. M. 1965. Inorganic forms of nitrogen. *In* C. A. Black (ed.) Methods of soil analysis, part 2. Agronomy 9:1179-0000. Am. Soc. Agron., Madison, Wis.
3. Chaminade, R. 1963. The effect of wheat straw of different degree of decomposition on soil fertility. Ann. Agron. (Paris) 14:5-12. (Biol. Abstr. 45:6043.)
3. Chandrasekaran, S., and T. Yoshida. 1973. Effect of organic acid transformations in submerged soils on growth of rice plant. Soil Sci. Plant Nutr (Tokyo) 19:39-45.
5. Ferguson, W. S., and B. J. Gorby. 1964. Effect of straw on availability of nitrogen to cereal crops. Can. J. Soil Sci. 44:286-291.
6. Gotoh, S., and Y. Onikura. 1970. The production of organic acids in the presence of rice straw in relation to the growth and yield of rice plant using pot culture technique. Bull. Kyushu Agric. Exp. Stn. 13:173-186. (Biol. Abstr. 51:11939 #121153.
7. ———, ———. 1971. Organic acids in a flooded soil receiving added rice straw and their effect on the growth of rice. Soil Sci. Plant Nutr. (Tokyo) 17:1-8.
8. Krantz, B. A., F. E. Broadbent, W. A. Williams, K. G. Baghott, K. H. Ingebretson, and M. E. Stanley. 1968. Research with nitrogen fertilizer emphasizes: fertilize crop—not crop residue. Calif. Agric. 22:6-8.
9. Laskowski, D. A., and F. E. Broadbent. 1970. Effects of chlorinated aliphatic acids on gas and volatile fatty acid production in anaerobic soil. Soil Sci. Soc. Am. Proc. 34:72-77.
10. Rai, K. D. 1965. Sorghum straw disposal in the central clay plain of the Sudan. J. Indian Soc. Soil Sci. 13:99-102.
11. Rao, D. N., and D. S. Mikkelsen. 1976. Effect of acetic, propionic, and butyric acids on young rice seedlings. Submitted for publication.
12. Sicar, S. S. G., and H. D. Bhowmick. 1940. Changes in constituents of rice straw produced by microorganisms present in soil suspension under aerobic, anaerobic and water-logged conditions. Indian J. Agric. Sci. 10:119-151.
13. Takijima, Y. 1964a. Growth inhibiting action of organic acids and absorption and decomposition of them by soils. Soil Sci. Plant Nutr. (Tokyo) 10:204-211.
14. ———. 1964b. Relations between production of organic acids in water-logged soils and the root growth inhibition. Soil Sci. Plant Nutr. (Tokyo) 10:212-219.
15. ———. 1965. Status of roots in the rhizosphere and the occurrence of root damage. Soil Sci. Plant Nutr. (Tokyo) 11:204-211.
16. ———, M. Shiojima, and Y. Arita. 1960. Effect of organic acids in root elongation and nutrient absorption of rice plants. J. Sci. Soil Manure Jpn. 31:441-446.
17. Williams, W. A., D. S. Mikkelsen, K. E. Mueller, and J. E. Ruckman. 1968. Nitrogen immobilizaiton by rice straw incorporated in lowland rice production. Plant Soil 28:49-60.
18. Yamane, I., and K. Sato. 1967. Effect of temperature on the decomposition of organic substances in flooded soil. Soil Sci. Plant Nutr. (Tokyo) 13:94-100.

CONCLUSIONS

The Ca status of serpentine soil was assayed by determining the percent Ca and the Ca/Mg ratio in four subclover plant parts. The results varied with plant part, stage of plant growth, and previous defoliation. The percent Ca and Ca/Mg ratios in new and old stems were insensitive as measures of Ca status since these values changed less in stems than in leaves over a wide range of Ca levels. Percent Ca in young leaves was the best measure of Ca status because critical values varied less due to stage of growth or clipping treatment than did percent Ca in old leaves or Ca/Mg ratios in young or old leaves.

LITERATURE CITED

Greenwood, E. A. N., and E. G. Hallsworth. 1960. Studies on the nutrition of forage legumes. II. Some interactions of calcium, phosphorus, copper and molybdenum on the growth and chemical composition of *Trifolium subterraneum*. Plant Soil 12:97-127.

Johnson, C. M., G. A. Pearson, and P. R. Stout. 1952. Molybdenum nutrition of crop plants. II. Plant and soil factors concerned with molybdenum deficiencies in crop plants. Plant Soil 4:178-196.

Jones, M. B., J. E. Ruckman, and P. W. Lawler. 1972. Critical levels of P in subclover (*Trifolium subterraneum* L.). Agron. J. 64:695-698.

Jones, R. G. W., and O. R. Lunt. 1967. The function of calcium in plants. Bot. Rev. 33:407-426.

Loneragan, J. F., and K. Snowball. 1969. Calcium requirements of plants. Aust. J. Agric. Res. 20:465-78.

Martin, W. E., J. Vlamis, and N. W. Stice. 1953. Field correction of calcium deficiency on a serpentine soil. Agron. J. 45:204-208.

———, and H. Jenny. 1948. Calcium deficiency in serpentine soils as revealed by absorbent technique. Science 107:549.

Vlamis, J. 1949. Growth of lettuce and barley as influenced by degree of calcium saturation of soil. Soil Sci. 67:453-466.

Walker, R. B., H. M. Walker, and P. R. Ashworth. 1955. Calcium-magnesium nutrition with special reference to serpentine soils. Plant Physiol. 30:214-221.