Soil Nutrient Balancing in Sustainable Vegetable Production

Results of 2000 season field trials, and evaluation of the first three years

A Final Report submitted to the Organic Farming Research Foundation, December 2000

Mark Schonbeck, Virginia Association for Biological Farming
439 Valley Drive NW, Floyd, VA 24091

Project Summary

The purpose of this project is to determine whether an unfavorable balance among soil potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) might be limiting vegetable production on some organic farms in the southeastern United States. These cation (positively charged) nutrients are held in exchangeable (plant-available) form on the soil's negatively-charged clay and humus particles. The Albrecht formula, utilized by "eco-farming" consultants and by many private soil test labs, recommends that the soil's cation exchange capacity (CEC) be occupies by cations in approximately the following ratios: Ca 65-75%, Mg 10-15%, K 2-5%, Na 0.5-3%, and hydrogen (H, or acid) 10-15%. This is called "base saturation ratio."

In Virginia and other southeastern states, many cultivated soils show Ca base saturation below 65%, with Mg and/or K well above their recommended ranges. This imbalance is believed to "tighten" the soil and degrade crumb structure, hamper aeration and drainage, cause surface crusting and hardpans, inhibit beneficial soil organisms and humus formation, aggravate weed, pest and disease problems, and hurt crop and livestock health. Applications of high calcium lime or gypsum to restore the balance are claimed to correct these problems; to enhance soil biological activity and organic matter levels; to increase availability of phosphorus (P), nitrogen (N) and other nutrients; and to improve produce flavor, nutritional value and shelf life.

Between 1998 and 2000, on-farm studies and a literature review were conducted to evaluate some of these claims. Field trials were conducted on five organic vegetable farms in Virginia and eastern Tennessee to determine whether applying Ca amendments to soils showing high Mg (average 24%) and slightly low Ca (average 63%) would benefit soil tilth, soil life or marketable vegetable yields. Treatments (*low-Ca* = control; *high-Ca* = Ca amendments applied four times between summer 1998 and summer 2000) were replicated three times at each site.

The high-Ca treatment shifted the average base saturation ratio to 70% Ca and 18%Mg, and slightly reduced K saturation. Vegetables grown on the amended soil had slightly higher foliar Ca and lower Mg levels. However, the high-Ca treatment had no detectable effect on soil organic matter, biological activity, crop uptake of N, P and micronutrients, abundance of weeds, incidence of disease or insect pest damage, or Brix (percent soluble solids, an index of produce quality) in broccoli or tomato. Broccoli yielded about 11% more in the high Ca treatment in the 2000 season, whereas treatment effects on tomato and squash yield have been inconsistent.

Soil bulk density (degree of compaction), moisture content, water infiltration rate (indicates drainage and porosity) and soil strength (resistance to root growth) were measured in fall 1999, and spring and fall 2000. When results from the five sites were *averaged*, the high-Ca treatment did not seem to affect any of these soil attributes. However, when results were considered *site by site*, some possible trends emerged at two sites. On a clay-loam soil in the Blue Ridge foothill region, the high-Ca treatment seems to have improved water infiltration and slightly loosened a pre-existing subsurface hardpan. Conversely, the high-Ca treatment apparently *tightened* hardpan and slowed water infiltration on a Tidewater sandy loam.

Two creek-bottom loam soils in the Appalachian region showed the "worst" base saturation ratios (Mg 27-28%, Ca 58-59%), but the best physical properties: low bulk density, high porosity and moisture-holding capacity, and no hardpan in the top 24 inches. Tilth has remained excellent regardless of Ca treatment. The clay soil at the fifth study site showed only a moderate Ca-Mg imbalance, but had a severe hardpan at 4 to 12 inches, and drained slowly after heavy rain. Ca applications have brought base saturation ratio close to the Albrecht formula, but have not improved soil tilth or loosened the hardpan.

A review of over 100 published studies and conversations with several soils consultants revealed evidence that proper cation balancing is inherently site specific. Most soils apparently do not need to conform to the Albrecht formula to be healthy and productive. Sandy Tidewater soils actually *require* somewhat higher Mg and K saturation for optimum crop nutrition. Some soil scientists warn that growers may be spending money and natural resources for lime or gypsum applications that their soils do not need. Both vegetable and agronomic crops thrive at a wide range of Ca and Mg levels, and soil tilth deteriorates only at extremely high Mg levels. However, too much soil K relative to Ca and Mg can tighten some soils, upset plant nutrition, and increase susceptibility of vegetable crops to some diseases and physiological disorders. Excessive soil K is a common problem in intensive vegetable production (both organic and conventional), and is often related to heavy use of off-farm inputs.

The current project was initially undertaken to validate the Albrecht formula in organic production in the southeastern US. Findings to date have led to a shift in focus toward developing a holistic, site-specific and resource-conserving approach to soil nutrient balancing. Often, growers can remedy cation balance by *reducing* inputs (e.g. excess K), and may not need Ca amendments to "correct" high soil Mg if soil and crops are already healthy. Information sheets have been developed to help to growers understand the cation balancing controversy, and to implement site-specific, cost-effective cation nutrient management on their own farms. Project findings were presented at three farm field days and one regional sustainable agricultural conference in 2000, and will be presented again at two more conferences in early 2001.

Additional funding will be sought to evaluate possible longer-term effects of the calcium treatments on soil health and marketable vegetable yields, and to refine cation nutrient management strategies.

Acknowledgements

This project has been conducted between 1998 and 2000 with support from the Organic Farming Research Foundation of Santa Cruz, Ca, and from the USDA Southern Region Sustainable Agriculture Research and Education (SARE) Producer Grant Program. The project also received an in-kind match from Soil Foodweb Inc. of Corvallis, OR, which conducted soil biology analyses for half the normal fees.

I would like to thank the following growers who participated in the field trials: Charlie and Miriam Maloney, Bo Holland, Ron Juftes and Polly Hieser, Joy Legendre, Ann Shrader, Cathy Guthrie, Chris Rasman, Ellen Polishuk and Hiu Newcomb. I am also grateful to Dr. Ray Weil, Professor of Soil Science at University of Maryland; Dr. Elaine Ingham soil micro-ecologist at Soil Foodweb, Inc; Steve Diver, Technical Specialist at ATTRA; and Margaret Merrill, reference librarian at Virginia Tech for technical assistance and support.

Mark Schonbeck, Project Coordinator

2. Introduction to the Topic

The purpose of this project is to determine whether an unfavorable balance of *potassium* (K), *sodium* (Na), *calcium* (Ca) and *magnesium* (Mg) in the soil might be limiting vegetable production on some organic farms in the southeastern United States. These *cation* (positively charged) nutrients, and the non-nutrient acid cation *hydrogen* (H), are held in *exchangeable* (plant-available) form on the soil's negatively-charged clay and humus particles. The soil's capacity to hold cations in this way is called the *cation exchange capacity*, or CEC. The percentage of the CEC occupied by each of the cations is called the *base saturation ratio*.

In the mid 20th century, Missouri soil scientist William Albrecht proposed an optimum base saturation ratio of 65-75% Ca, 10-15% Mg, 2-5% K, 0.5-3% Na and about 10-15% H, based on his research into crop and livestock nutrition (Albrecht, 1975; Albrecht, 1989). Many organic farming and eco-farming consultants utilize this "Albrecht formula" in making soil management recommendations (Cantisano, 1992; Kinsey & Walters, 1993; Luebben, pers. commun.; Young, 1999).

Many cultivated soils in Virginia and other southeastern states have Ca base saturation below 65%, with K and/or Mg saturations well above their recommended ranges. In addition to the direct nutritional effects cited by Albrecht, it is known that Ca ions adsorbed onto soil clays promote aggregation (crumb structure), whereas K, Na and (to a lesser degree) Mg tend to disperse soil aggregates. Thus low Ca and high Mg or K are believed to "tighten" the soil, degrade crumb structure, hamper aeration and drainage, and promote surface crusting and hardpans. These soil conditions can inhibit beneficial soil organisms and humus formation, weaken crops, aggravate weed, pest and disease problems, and reduce produce quality. Growers who use the Albrecht formula apply high-calcium limestone or gypsum (calcium sulfate) to add Ca and displace excess Mg and K from the CEC. Benefits claimed for this practice include:

- improved soil tilth, moisture capacity, aeration and drainage
- less crusting and compaction
- stimulation of beneficial soil life and humus formation
- more balanced and diverse soil life, fewer root pathogens
- increased availability of phosphorus (P), nitrogen (N) and other nutrients
- enhanced crop uptake of nutrients, better crop nutrition
- increased crop resistance to pests, diseases and environmental stresses
- fewer weeds (seeds degraded more rapidly by soil life)
- higher marketable yields
- produce with better nutritional value, higher soluble solids content (Brix)
- longer shelf life

Many soil scientists reject the base saturation ratio approach to soil management as unnecessary and potentially wasteful (Eckert, 1987; Goldstein, 1990; Liebhardt, 1981, Weil, pers. commun.). They cite a lack of evidence that Ca amendments improve soil conditions or crop yields, except when liming is required to correct soil pH. Similarly, results from the 1999 season of the current study did not yield such evidence (Schonbeck, 2000a). Farm consultants who use the Albrecht formula have not validated it with properly controlled field trials (Weil, pers. commun.), yet they report a high degree of grower satisfaction with this system (Kinsey & Walters, 1993, Luebben, pers. commun.; Putney, pers. commun.; Young, 1999; Zimmer, 1999).

An in-depth literature review conducted in 1999 revealed the *site-specific* nature of soil cation nutrient balance. Some soil clays, such as bentonite, montmorillonite and vermiculite, bind Ca much more tightly than do kaolinite or humus (Allaway, 1945; Mehlich 1942, 1946). Mica clays are intermediate in Ca binding. Therefore, soils rich in bentonite or vermiculite need a higher %Ca base saturation to ensure adequate plant-available Ca, than do soils whose CEC is composed primarily of kaolinite and humus (Mehlich & Colwell, 1943). Unlike the midwest region where Albrecht did much of his research, kaolinite is the dominant clay in most southeastern US soils (Brady & Weil, 1999). Furthermore, sandy Tidewater soils with low CEC may require higher Mg and K base saturation than Albrecht recommended to ensure sufficient crop-available Mg and K (Kinsey & Walters, 1993; Mehlich, 1946).

Gypsum is used to ameliorate soil tilth primarily on saline or high-Na soils (Greene & Ford 1985, Grierson, 1978), which rarely occur in the southeastern US. In non-saline soils, little correlation has been found between Ca base saturation and soil aggregation (Baver et al., 1972), and the clay-dispersing effect of Mg is usually negligible unless the Mg base saturation exceeds that of Ca (Curtin et al, 1994).

Some highly weathered soils in the southeast have strongly acid subsoils with very low Ca and toxic levels of aluminum (Al) that severely curtail root growth (Sumner, 1993). In this case, adding gypsum to provide Ca and reduce Al, may allow deeper root growth and better yields. On sandy, low-CEC soils, however, gypsum can aggressively leach out Mg and K, resulting in crop deficiencies in these elements (Sumner, 1993, Syen-Omar & Sumner, 1991).

Whereas crops seem to tolerate a wide range of Ca:Mg ratios (Key *et al,* 1962; Martin & Page, 1969; McLean, 1972; Simson *et al.,* 1979), the Ca:K ratio may be more critical for some vegetables. A combination of low Ca and high K has been related to increased blossom end rot in tomato (Bar-tel & Pressman, 1996), blackheart in celery (Geraldson, 1954), cavity spot in carrot (Maynard, *et al.*, 1963) and other Ca-stress disorders (Kirkby, 1979). These disorders usually result from temperature or soil moisture fluctuations that induce a *localized* Ca deficiency in the affected part, even when soil Ca is adequate. Excessive soil K can restrict plant uptake of Ca, and thereby contribute to Ca stress disorders. Similarly, ample available Ca can enhance crop resistance to some bacterial and fungal diseases, but high K may cancel this effect in some cases (Forster & Echandi, 1975, Volpin & Elad, 1991, Yamazaki & Hoshina, 1995).

Cation "imbalances" have been claimed to inhibit beneficial soil organisms (Kinsey & Walters, 1993), but little research has been done on the effects of base saturation ratio on soil life. Conversely, healthy soil life can "buffer" the soil so that crops can thrive despite non-optimum pH or nutrient levels on a soil test. Recent research demonstrates the vital role of soil organisms in providing the crop with N, P, K, Ca and other nutrients (Ingham, 1999, Phelan, 1997). Also, gypsum and subsoiling relieve hardpan most effectively if followed by deep rooted crops that bring organic matter and microbial activity into the subsoil (Sumner, 1993).

These findings suggest that applying a single base saturation ratio "formula," to all soils can lead to unnecessary and costly amendment applications in many cases. Providing "sufficient but not excessive" levels of each nutrient may be more cost-effective for most farms (McLean, 1977). At the same time, some soil problems (*e.g.* acid subsoil), and crop production problems (*e.g* .vegetable Ca stress disorders) may merit attention to soil cation balance. There exists a need for sound practical guidelines for a *site-specific* and *resource-conserving* approach to cation nutrient balancing, set within a context of managing soil as a living system. The current project was carried through its third season (2000) with this overall goal in mind.

Project Objectives

The overall objectives of the project are: (1) to document the long term (5 year) effects of adjusting soil base saturation ratio toward the Albrecht formula on soil properties and vegetable crop production on five organic farms; and (2) to develop, disseminate and periodically update practical guidelines to help growers determine *whether* and *how* to implement soil cation balancing measures on their farms. Specific objectives for the 2000 season (plain text), with comments (*italics*) on progress toward, and changes in, those objectives follow.

A. to document the effects on soil exchangeable K, Mg and Ca, and on crop foliar nutrient levels, of two treatments designed to produce different soil base saturation ratios in field experiments at five farms. *Completed.*

B. to collect third-season data on soil physical properties in the two treatments at each farm. *Completed. Soil biological properties also measured.*

C. to evaluate treatment effects on marketable yields, quality, and Ca-stress disorder symptoms of three crops known to have high Ca requirements: tomato, broccoli and Chinese cabbage. *Yield and quality data taken for tomato (2 sites), broccoli (4 sites) and winter squash (1 site). Insufficient Chinese cabbage was established in plots to collect data.*

D. to evaluate the effects of low-K and high-K mulches on soil base saturation ratio and asparagus yields at one farm. *Base saturation ratio and soil strength measured. No yield data taken because of time constraints.*

E. to continue case studies at three farms, in which soil management practices based on cation nutrient balancing and organic matter optimization are implemented in selected fields. *Limited monitoring only in these fields, again due to time constraints.*

F. to continue to develop and refine soil cation balancing guidelines. *Information sheets revised and published Dec. 1, 2000. Copies attached.*

G. to communicate interim results and findings to growers and agricultural professionals through farm field days, presentations at conferences, semi-annual written project updates, and information sheets. *Completed.*

Materials and Methods

Replicated Field Trials

Replicated field trials were established in 1998 at five organic vegetable farms in Virginia and eastern Tennessee. Low-Ca and high-Ca treatments are replicated three times at each site. Plots received four experimental amendment applications between spring 1998 and spring 2000. Plots measure at least 20 ft x 30 ft, except at Site 2, where the small scale of operation necessitated a plot size of 10 ft x 25 ft. Following is a brief description of each site.

*Site 1***.** Dayspring Farm, King and Queen Co., VA is located in the Tidewater region. The experimental field is on a level, sandy loam with low organic matter and CEC. It has been under organic vegetable production with winter cover cropping since 1997, and had been in hay (grass + alfalfa) for several years prior to that. A strong, persistent hardpan exists between 6 and

12 inches depth. It appears to be associated with a long history of conventional agriculture and heavy machinery prior to 1990 under previous ownership.

Site 2. Screech Owl Farm in Nelson Co., VA is located in the Blue Ridge foothills. The experiment is on a loam to clay-loam soil, on a ~5% south-facing slope, that has been in organic vegetable production with winter cover crops since 1996. Topsoil organic matter and tilth have been built up, but a moderately strong hardpan persists between 6 and 12 inches, again possibly resulting from heavy farm machinery traffic under previous ownership.

Site 3. Seven Springs Farm in Floyd Co., VA is located in the Appalachian region, elevation *ca.* 2,700 ft. The experiment is on a level creek bottom loam with high organic matter and fertility. The soil has a high content of river stones, but is well drained and free of hardpan. It has been in organic/biodynamic vegetable production with winter cover crops since 1995.

*Site 4***.** Abundant Dawn in Floyd Co., VA is in the Appalachian region at *ca.* 2200 ft elevation. The experiment is on a level river bottom loam with physical properties similar to Site 3, but with fewer stones and somewhat lower organic matter, P and K levels. The field has been an organically managed homestead garden for at least 12 years.

Site 5. Holley Creek Farm in Greene Co., TN is located in the Nolichuckey River valley. The experiment is on a nearly-level field with a clay to clay-loam soil with a long history of conventional tobacco production and heavy machinery traffic that depleted organic matter and degraded soil structure. Beginning in fall 1995, it was converted to organic vegetable production with winter cover crops, and the use of municipal leaves as mulch. Drainage is somewhat slow, and a severe hardpan persists at a depth of 4 to 12 inches.

Table 1 shows results of a standard soil analysis (A & L Eastern Agricultural Laboratories, Richmond, VA) and a texture analysis for each site, conducted prior to the initial experimental treatments in 1998.

Table 1. Soil texture analysis and soil test results for each experimental site in 1998.

		Texture (%):				%		ppm:				
Site & soil type		sand	silt	clay	pH	OM	CEC	P-1[a]	P-2	K	Mg	Ca
1	sandy loam	67	15	18	6.4	1.4	2.4	39 h	44 h	70 h	52 h	320 m
2	loam/clay loam	43	32	25	6.9	3.7	7.8	46 vh	68 vh	230 vh	213 vh	1070 h
3	loam	44	38	18	6.3	7.1	7.8	29 h	76 vh	200 vh	247 vh	880 m
4	loam	42	40	18	6.4	4.9	7.9	14 L	40 m	121 h	264 vh	930 m
5	clay loam/clay	30	28	42	6.0	2.9	6.5	65 vh	86 vh	113 h	156 vh	780 m

	% base saturation:				micronutrients, ppm:					
Site	K	Mg	Ca	H	S	Zn	Mn	Fe	Cu	B
1	7.4	17.8	65.9	8.9	11 m[b]	1.0 vl	11 m	11 h	0.4 L	0.4 L
2	7.5	22.7	68.4	1.4	11 m	5.4 h	59 vh	45 h	0.8 m	0.8 m
3	6.6	26.4	56.5	10.6	11 m	5.6 h	18 m	32 h	0.8 m	1.1 m
4	3.9	28.0	59.1	8.9	7 L	6.5 h	40 h	40 h	2.8 h	0.8 m
5	4.5	20.0	60.1	15.4	11 m	4.3 h				0.8 m

---

[a] P-1 = available phosphorus; P-2 = reserve phosphorus; K = potassium, Mg = magnesium, Ca = calcium, S = sulfur, Zn = zinc, Mn = manganese, Fe = Iron, Cu = copper, B = boron.

[b] Nutrient levels: vl = very low; L = low, m = medium, h = high, vh = very high.

Experimental amendments were applied in 1998, spring and fall 1999, and spring 2000 at each site as follows. When soil pH was 6.3 or below, the high-Ca treatment received calcitic limestone and the low-Ca treatment received dolomitic limestone at equal rates. Lime was applied at 500 to 2,000 lb/acre depending on soil pH and CEC. When soil pH was 6.4 or higher, the high-Ca treatment received gypsum (500 to 1,000 lb/acre), and the low-Ca treatment received no amendment, with one exception. At Site 1, the low-Ca treatment received sul-po-mag (potassium-magnesium sulfate) at 500 lb/acre in spring of 2000, since K and Mg levels were possibly sub-optimal on this sandy loam soil. Soil tests verified substantial differences between treatments in cation balance as of September 2000. Total amendment applications and base saturation ratios for low-Ca and high-Ca treatments are shown in Table 2.

Table 2. Total amendments applied 1998-spring 2000, and fall 2000 soil test results for low-Ca and high-Ca treatments at each site.

		Cation			ppm:		% base saturation:		
Site	Treatment	amendments applied[a]	pH	OM	P-1	S	K	Mg	Ca
1	Low-Ca	spm 500, grn 1040	6.5	1.9	53	5	7.8	18.9	64.7
	High-Ca	gps 2000, grn 1040	6.3	2.0	58	5	6.1	11.2	70.9
2	Low-Ca	none	7.0	4.0	45	5	8.0	21.4	70.0
	High-Ca	gps 3000	6.9	4.1	39	14	6.7	16.6	74.8
3	Low-Ca	none	6.5	5.7	19	10	6.6	26.7	59.0
	High-Ca	gps 2500	6.5	5.6	19	23	6.2	22.9	63.1
4	Low-Ca	dol 1230	6.3	3.3	11	7	3.4	28.1	57.7
	High-Ca	cal 1230, gps 1500	6.4	4.6	9	15	3.2	21.0	66.5
5	Low-Ca	dol 2720	6.6	3.8	52		6.5	23.9	63.0
	High-Ca	cal 2800, gps 500	6.7	3.8	61		5.8	16.4	72.8
Mean of 5 sites:									
	Low-Ca		6.6	3.7	36	8	6.5	23.8	62.9
	High-Ca		6.6	4.0	37	14	5.6[b]	17.6[b]	69.6[b]

[a] figures give lb/acre. dol = dolomitic limestone; cal = calcitic (high-calcium) limestone; gps = gypsum; spm = sul-po-mag; grn = greensand.

[b] differences between treatments are statistically significant at the 5% probability level.

Other mineral amendments were applied equally to both treatments as follows. Borax was applied at 5 lb/acre at Sites 1 (1998) and 4 (1998 and 2000) to remedy a low boron (B) level. Greensand was applied at 1,040 lb/acre at Site 1 in fall 1999 after both soil and tomato foliar tests showed low K. Rock phosphate was applied at 500 lb/acre at Sites 1, 2, 3 and 4 in 1998 in the belief that existing soil P levels were below optimum. Since then, however, we learned that a P-1 levels of 20-25 ppm may be sufficient (Magdoff & Van Es, 2000).

At all sites, organic matter management, compost and organic fertilizer applications, and tillage were conducted according to grower's normal practices. Organic inputs for the 2000 season are shown in Table 3.

Table 3. Organic inputs at each site during the 2000 season

Site	Cover Crops	Mulches	Compost	Nutrients (lb/acre) in compost application: N – P – K – Ca – Mg
1	Rye + vetch (disked at 18-24 in.)		3 tons/acre	not analyzed[a]
2	Rye + vetch (tilled at ~12 in.)	~2 in. hay + tree leaves	8 tons/acre	120 – 55 – 41 – 255 – 48
3	None		10 tons/acre	147 – 62 – 103 – 258 –126
4, early crops:	None	~ 3 in. hay	3 tons/acre[b]	34 – 9 – 22 – 27 – 11
4, late crops:	Rye + vetch (sickled at 36-48 in.)	cover crop, hay in tomato row	1.3 tons/acre in planting holes	not analyzed[c]
5	Rye & vetch (strip tilled)	~ 3 in. tree leaves in crop row, and over entire field in fall		

[a] compost based on 10% poultry litter and 90% tree leaves and chipped brush.
[b] aged horse manure with sawdust bedding.
[c] composted kitchen scraps and yard waste.

During the 2000 season, broccoli and other brassicas were grown at Sites 1, 2 and 3, and tomatoes were grown at Site 5. At Site 4, the plots were divided into four beds, which have been in a four-year rotation of onions, brassicas, tomatoes and winter squash since 1998.

Soil analyses were conducted in spring of 2000. For each plot, eight cores (0-6 inches) were taken and mixed throughly in a clean bucket. Subsamples were sent to A&L Eastern Agricultural Lab to determine SOM, pH, CEC and major nutrients; and to Dr. Raymond Weil at

University of Maryland to determine active (permanganate-oxidizable) organic matter. Active organic matter is a good index of overall soil quality (Islam & Weil, 2000). Additional samples (eight cores per plot, 0-3 inch depth, pooled) were submitted for a complete soil foodweb analysis, including active and total bacteria; active and total fungi; amoeboid, flagellate and ciliate protozoa; and beneficial (microbial-feeding) and pest (root-feeding) nematodes (Soil Foodweb, Inc., Corvallis, OR). The standard soil analysis was repeated in fall of 2000.

The following properties were measured in each plot in May-June and again in September-October, 2000: soil strength, infiltration rate, bulk density, moisture-holding capacity and soil respiration. Earthworms populations were recorded in June and September at Site 4.

Soil strength was measured with a Dickey-John penetrometer. Average depth at which a resistance of 200 psi was reached, and average maximum resistance between 0 and 12 inches were estimated, based on six probes per plot. When deeper penetration was practical, the minimum and maximum resistance within the 12 to 24 inch depth range were recorded, and a “mean” resistance was calculated as the average of these two values.

Infiltration rate, bulk density, moisture content, and respiration were measured as described in USDA (1999) (See Plates 2 and 3 in Addenda). For infiltration rate, one-inch increments of water were added to a 6-inch-diameter, single-ring infiltrometer inserted to a depth of 3 inches. The time required for the second inch of water to soak into the ground was recorded. Infiltration was measured at the soil surface, except that in fall of 2000, soil was carefully excavated to a depth of 6 inches at Site 1, and 2 inches at Site 3, because recent tillage had left the surface layers too rough to obtain a meaningful measurement. Bulk density and moisture content were measured on cores from 0-4 inch depth. The volume of each core was measured (to ±3% error), then the core was weighed, oven-dried at *ca* 180°F, and reweighed to determine percent moisture and dry bulk density.

Soil respiration was determined *in situ* by inserting a 6-inch (diam.) x 5 inch (ht.) ring into the soil to a depth of *ca.* 3 inches, and covering the ring with an airtight lid. After a 1 to 2 hour incubation, carbon dioxide accumulation was determine using a Draeger tube and syringe apparatus. Respiration was calculated according to formulas described in USDA (1999).

Earthworm populations were estimated at Site 4 by sampling two randomly selected quadrats (1 ft. x 1 ft. x 6 in. deep), from each plot in June 2000, and sampling one quadrat in September. Worms were counted by the hand-sorting method.

Additional measurements were conducted at three sites to explore soil conditions below the tillage layer. At Site 1, bulk density and moisture content were measured at 6-10 inches (within the hardpan layer) and at 12-16 inches, and a standard soil test was conducted at 12 to 18 inches. At Sites 2 and 4, bulk density and soil moisture were measured at 6-10 inches. Visual observations of the presence-absence of roots and macro-pores in the subsoil were also recorded.

Foliage samples were collected from broccoli at the mid-growth stage at Sites 1-4, and from tomato at early fruit set at Sites 4 and 5 according to laboratory instructions (A&L Agricultural Laboratories, undated), and submitted for nutrient analysis. Total soluble solids (Brix) was measured with a hand-held refractometer, for stalks of broccoli side-heads (5 samples per plot) at Sites 1, 3 and 4, and for tomato (4 fruits per plot, blended together) on two harvest dates at Site 4. For winter squash, shelf life was evaluated at Sites 3 and 4 in the 1999 season by storing ten apparently-sound fruit from each plot at room temperature until early winter.

During the growing season, participating growers took observations on pest, disease and weed problems in the experimental plots, and recorded any apparent treatment-related effects.

Marketable and total yields were recorded in 2000 for broccoli (Sites 1, 2, 3 and 4), tomatoes (Sites 4 and 5) and winter squash (Site 4). Percent marketable yield was computed as: 100 X (marketable yield)/(total yield). Plantings of Chinese cabbage (Sites 3 and 4) were insufficient for yield measurements, and onions failed at Site 4 because of root maggots.

Data were subjected to standard statistical analyses across sites to evaluate overall treatment effects. Site-specific trends were evaluated qualitatively, since replication at a single site (3 reps x 2 treatments) was insufficient for meaningful statistical analysis

Mulching Trial

A second trial was established in 1998 in a recently-planted asparagus field, to determine whether type of organic mulch used can influence cation balance or soil physical properties. Plots, each consisting of two rows x 20 ft, were randomly assigned to receive either hay mulch or municipal leaves, with three replicates. Mulches were applied annually in 1998-2000. In September 2000, soil samples were taken for standard nutrient analysis, and soil strength at 0-24 inches depth was tested with the penetrometer (4 probes per plot).

Case Studies

Standard soil tests were conducted annually in 1998-2000 for three additional fields at Site 3 (Appalachian region), two fields at Potomac Vegetable Farms in Purcellvile, VA (Blue Ridge foothills), and two fields at Potomac Vegetable Farms in Vienna, VA (near Washington DC). In addition, soil samples were taken in 1999 and 2000 for three fields at Site 2 (Blue Ridge foothills) at the grower's request. Test results were interpreted, and cation management recommendations were made based on project findings.

Literature Review

Most of the literature review was conducted during the 1999 season (Schonbeck, 2000). About 20 additional research reports were reviewed during the current season, and the annotated bibliography was updated. Copies were provided to project participants Steve Diver, Margaret Merrill, Dr. Raymond Weil and Dr. Elaine Ingham for review. Results of this aspect of the project were covered above in "Introduction to the Topic."

Project Results and Discussion

Replicated Field Trials

Application of Ca amendments (gypsum and/or calcitic lime) brought soil base saturation ratios substantially closer to the guidelines proposed by Dr. William Albrecht. Four applications of calcitic lime and/or gypsum, totaling 2000 to 3300 lb/acre, lowered Mg base saturation levels by 4-8 percentage points, raised Ca saturation by a similar amount, and reduced K saturation by about one percent (Table 2). However, when results were averaged across the five study sites, no net benefits to other soil properties were observed. In particular, *soil physical properties related to tilth showed no apparent response to the Ca treatment* (Table 4). Soil strength values below 200 psi are considered favorable to root growth and function, and values above 300 psi generally restrict root growth. Strong hardpans occurred at about a 6-inch depth at Sites 1, 2 and 5, resulting in high maximum soil strength, regardless of treatment. Topsoil bulk densities and water infiltration rates at all sites were generally favorable, and again unaffected by treatment.

Soil chemical and biological properties showed no clear benefits from the Ca treatment. As expected, Ca amendments augmented soil Ca and reduced Mg, and gypsum caused a sharp but temporary increase in S. However, Ca treatment did not enhance organic matter or available P (Table 2). Field respiration and active organic matter levels were essentially the same in low-Ca and high-Ca treatments (Table 5). Apparent differences in populations of fungi, bacteria, protozoa, and both pest and beneficial nematodes were too small to indicate a treatment effect.

At Site 4, June earthworm counts were 43/sq. ft. in the high-Ca treatment versus 27/sq. ft. for low-Ca. However, this trend did not hold in September: 34 for high-Ca versus 37 for low-Ca.

Table 4. Effects of Ca treatments on soil physical properties [a]

	Soil strength 200 psi at (depth, in.):	Soil strength max. psi at 0-12 inches	Dry bulk density	Moisture content (%)	Infiltration (minutes/inch)
Low-Ca	6.4	410	1.17	23.4	3.5
High-Ca	6.1	410	1.18	23.2	3.6
L.S.D.$_{0.05}$[b]	0.8	40	0.03	1.0	2-fold[c]

[a] Mean across five study sites and three sampling dates (fall 1999, spring and fall 2000), except that soil strength was measured at four sites in spring 2000, and three sites in fall 2000.

[b] Least significant difference at 5% probability level. *Apparent treatment differences smaller than this are considered "non-significant," or likely to have occurred by chance.*

[c] Infiltration data were so variable that a log-transformation was used for statistical analyses. A two-fold difference between treatments would be just significant at the 5% probability level.

Table 5. Effects of Ca treatments on soil biological properties[a]

	Active O.M., ppm	Respiration, lb C/acre-day: late spring	Respiration, lb C/acre-day: early fall	Microbial biomass, ppm dry soil: --Bacteria-- active	Microbial biomass, ppm dry soil: --Bacteria-- total	Microbial biomass, ppm dry soil: ---Fungi--- active	Microbial biomass, ppm dry soil: ---Fungi--- total
Low-Ca	1,680	26.8	22.4	25.6	190	24.8	116
High-Ca	1,680	26.9	21.9	28.0	182	22.8	113
L.S.D.$_{0.05}$[b]	132	4.8	2.8	9.7	35	11.7	32

	Protozoa, 1000s per gram soil: Flagellates	Protozoa, 1000s per gram soil: Amoebae	Protozoa, 1000s per gram soil: Ciliates	Nematodes, individuals per gram soil: Total	Nematodes, individuals per gram soil: Root feeders (pests)
Low-Ca	35.5	107.2	0.93	3.3	0.65

High-Ca	38.0	107.2	1.12	4.4	0.74
L.S.D.$_{0.05}$	1.7-fold[c]	2-fold	3-fold	1.6	0.57

[a] Mean across five sites
[b] Least significant difference at 5% probability level
[c] Protozoan counts were highly variable; thus data were log-transformed for statistical analysis.

The high-Ca treatment consistently increased broccoli foliar Ca levels and reduced foliar Mg, but the changes were relatively small (Figure 1). Notably, foliar Ca levels were near optimum at all four sites, regardless of treatment. Foliar N, P and K levels were ample, and were not affected by Ca treatment. The high-Ca treatment pushed foliar S to very high levels, almost certainly because of the gypsum used to supply Ca. At Site 1, where the low-Ca plots received sul-po-mag in spring of 2000, *both* treatments resulted in extremely high foliar S (>2%).

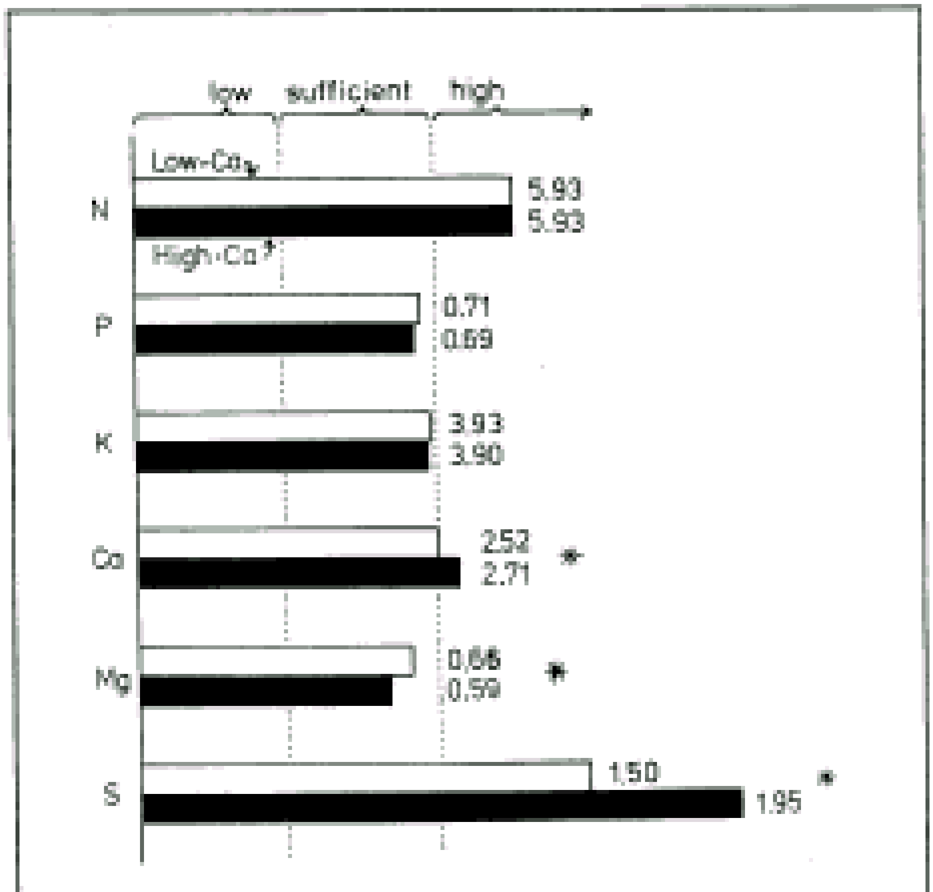

Figure 1. Broccoli foliar nutrient levels in low-Ca and high-Ca treatments, relative to reported sufficiency ranges *(A&L Agricultural Laboratories, undated).* **Mean for spring broccoli grown at Sites 1, 2, 3 and 4 in the 2000 season.**
*** indicates treatment effect is statistically significant ($p < 0.05$)**

Tomato foliar tests at Site 4 showed very high Mg levels, with Ca, N, P and K near the lower end of their sufficiency ranges (Table 6). At Site 5, tomato foliar Ca was definitely low. The high-Ca treatment enhanced foliar Ca and reduced foliar Mg at both sites, but the changes were fairly small, especially at Site 5. The gypsum applied to high-Ca plots raised foliar S levels significantly, but not to excessive levels.

Tomato foliage samples were taken somewhat later in crop development (early fruit set) than recommended by the laboratory (early flowering). This may have played a role in the apparently low N, P and K values. However this is probably not true for Ca, since Ca is not translocated from leaves to fruit as are other nutrients (Kirkby, 1979).

Table 6. Tomato foliar nutrient levels (% of dry weight) in low-Ca and high-Ca treatments at Sites 4 and 5, compared to reported sufficiency ranges.

	N	P	K	Ca	Mg	S
Site 4						
Low-Ca	4.27	0.35	2.62	2.87	1.18	0.60
High-Ca	4.28	0.35	2.74	3.20	0.97	1.00
Site 5						
Low-Ca	3.66	0.59	3.18	1.69	0.45	0.73
High-Ca	3.52	0.54	3.11	1.88	0.39	0.91
Sufficiency ranges	4.00-6.00	0.25-0.75	2.90-5.00	2.50-4.00	0.40-0.60	0.40-1.20

Effects of Ca treatment on marketable vegetable yield were inconsistent. In the 1999 season, the Ca amendments had little effect on cabbage or winter squash yields, and seemed to *reduce* tomato yield at two sites (Figure 2a). In 2000, the high-Ca treatment apparently enhanced broccoli yield at two out of four sites in 2000 (Figure 2b). When data were analyzed across all four sites, broccoli yields averaged about 11% higher in the Ca-amended plots, and the difference was *just* significant at the 5% probability level. At site 4, broccoli, tomato and butternut squash *all* showed higher average marketable yields in the high-Ca treatment,. At site 5, yields were measured only for a late planting of tomato, which became severely blighted before maturity. An earlier tomato planting in the experimental plots gave much better yields.

Several insect pest and disease problems were observed in the vegetable crops during the 2000 season. Tomato crops at Sites 4 and 5 developed fungal diseases (primarily early blight caused by *Alternaria solani*), which affected foliage and a small percentage of fruit. Broccoli at Site 1 "buttoned" prematurely, resulting in very small heads, likely as a result of sharp temperature fluctuations during the spring. At Site 4, slugs attacked young broccoli plants in May, and damaged many tomato fruit in August and September. Also, the cut stems of broccoli heads showed internal cracking and slight browning at Site 4, a symptom of possible boron deficiency. We did not observe any differences between Ca treatments in the severity of any of these problems.

Percent weed cover was estimated in spring and summer of 2000 at Sites 1 and 4. Again, no differences between Ca treatments were detected.

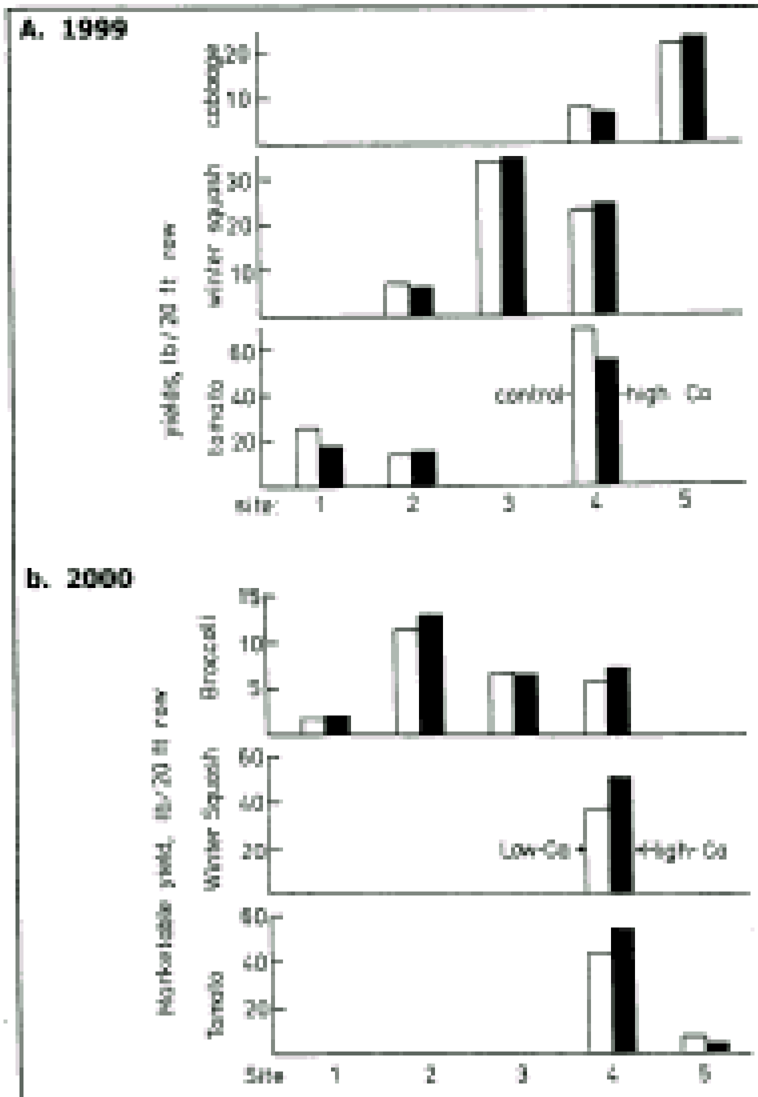

Figure 2. Marketable vegetable yields in low-Ca treatment (open bars) and high-Ca treatment (solid bars) at five sites. A – cabbage, butternut squash and tomato in 1999. B – broccoli, butternut squash and tomato in 2000.

The high-Ca treatment did not enhance the total soluble solids content (Brix) of tomato or broccoli, and did not significantly improve percent marketable yield (Table 7). Brix values of both crops were much lower in 2000 than in 1999. This was most likely related to the cool, moist conditions during summer 2000, and not to soil cation balance. Butternut squash grown in low-Ca and the high-Ca treatments showed very similar percent marketable yield and shelf life.

Table 7. Brix (% soluble solids), % marketable yield, and shelf life in tomato, broccoli and winter squash grown in low-Ca and high-Ca treatments in 1999 and 2000.

	Low-Ca	High-Ca	L.S.D.$_{0.05}$ [a]
Broccoli:			
Brix, 1999, Site 4	6.4	6.6	0.6
Brix, 2000, Sites 1, 3, 4	5.4	5.3	0.2
% marketable yield, 2000, Site 4	63	67	10
Tomato:			
Brix, 1999, Sites 1 and 4	6.7	6.7	0.4
Brix, 2000, Site 4	4.1	4.0	0.1
% marketable yield, 2000, Site 4	62	71	29
Butternut Squash:			
% marketable yield, 1999, Sites 3 & 4	80	80	
% sound after 2 months storage, 1999	75	76	
% marketable yield, 2000, Site 4	74	74	

---

[a] Least significant difference at 5% probability level.

Mulch Experiment at Site 2

Asparagus beds mulched with municipal leaves showed somewhat lower K base saturation and soil strength, than those mulched with hay (Table 8). Organic matter and CEC averaged higher with the leaves, although the trend was not consistent across all three replicates. Both treatments showed excessive Ca levels, probably from a heavy application of high-Ca lime in 1997. Surprisingly, the leaf mulch has also pushed available P levels very high. Since the leaves themselves contain relatively little P, it is possible that this mulch fostered micro-organisms that solubilized P from rock phosphate applied at the time the asparagus was planted.

Table 8. Base saturation ratio, soil organic matter and P levels, and soil strength, in asparagus beds mulched with municipal leaves or with hay.

	% OM	pH	CEC	avail. P	% base saturation: K	Mg	Ca	Soil strength: 200 psi at (depth, in):	max psi at 0-12 inches
Leaves	4.0	7.2	10.4	89	4.1	11.0	84.9	8.5	240

Hay	3.2	7.0	8.6	27	5.2	9.0	82.9	5.4	280

An Evaluation of Different Measures of Soil Health

Any soil test or measurement must meet two criteria in order to be a useful index of the impact of experimental treatments or management practices. First, it must accurately reflect an important aspect of soil health or quality. Second, the amount of random variability (indicated by the "least significant difference" shown in data tables) in the measured parameter must not be so great as to obscure actual treatment effects, or give misleading "false positives."

Soil and foliar nutrient analyses showed fairly low random variability, which allowed us to verify treatment effects on Ca, Mg and S levels in both soil and crop, and to demonstrate that the experimental treatment had little effect on crop uptake of N, P or most other nutrients.

The total soil organic matter shown on soil test reports does not always correlate with desirable biological activity or humus levels. The recently-developed assay *for active organic matter* has been shown to correlate well with soil quality, with values above 1,600 ppm indicating good conditions, and values below 1,000 ppm indicating possible problems (Islam & Weil, 2000). Random variability in this parameter was quite low (Table 5), so that if the Ca amendments had enhanced active organic matter by just 8 to 10 percent, our experimental design would likely have detected this effect. Bulk density (a widely accepted index of the degree of soil compaction) and soil moisture content showed even lower random variation. Thus, the lack of detectable response in these three soil properties to the Ca treatment has provided useful information. Similarly, the percent soluble solids (Brix) shows low variability (Table 7); thus any treatment effects on this crop quality index should be readily detected.

Laboratory analyses of populations of soil organisms showed high random variability, especially for protozoa (Table 5), which complicated our efforts to estimate treatment effects on the web of life in the soil. An experimental would have to enhance (or inhibit) bacterial or fungal biomass by 30 to 40 percent in order to be detected through this procedure. Field measurements of soil respiration can be complicated by the presence or absence of plant roots or larger soil organisms (Weil, pers. commun.). However, this procedure attempts to evaluate the actual rate of soil biological activity with minimum disturbance, compared to laboratory procedure. Random variability was moderate, so that treatment effects of 20 to 25 percent could be detected (Table 5). Apparently, the Ca treatment had little or no impact on soil respiration.

Penetrometer measurements can be misleading, because dry soil conditions can give very high readings, and because the implement may not detect worm channels or other pores that allow roots and moisture to penetrate an otherwise "hard" layer (Weil, pers. commun). In the current study, at least four readings were taken per plot, and were conducted at least twice at each site while the soil was moist. A consistent pattern emerged: strong hardpans at Sites 1, 2 and 5, and little or no hardpan at Sites 3 and 4. Restricted root growth within and below the hardpan was confirmed by digging to a depth of 14 inches at Site 1. Individual readings varied widely, but taking the average of multiple readings reduced random variation to manageable levels (Table 4).

Rate of water infiltration into the soil has been recommended as a good indicator of tilth (Weil, pers. commun). However, we found that this measurement can be drastically affected by recent tillage, and by the presence or absence of earthworm or other animal channels within the infiltrometer ring. Random variability is very high, but can be reduced somewhat, either by conducting measurements when the soil had not been tilled for several months, or by carefully excavating to a level surface below the tillage layer. Multiple measurements per plot can also help, but this strategy is limited because the procedure is somewhat time consuming.

A Consideration of Findings at Each Site

Whereas the high-Ca treatment had little effect on soil properties averaged across the five study sites, some trends were observed that indicate possible *site-specific* treatment effects.

Site 1, located on a Tidewater sandy loam, shows signs of possible *detrimental* effects of gypsum (Table 9). In fall of 2000, the high-Ca plots (amended four times with gypsum) showed higher soil strength, both within and below the hardpan, than in the low-Ca plots (amended once with sul-po-mag). Water tended to infiltrate more slowly in the gypsum-amended plots on two of three measurement dates. The soil foodweb analysis showed trends toward lower bacterial, fungal and mycorrhizal activity in the high-Ca treatment. Ciliate protozoa were more abundant in the high-Ca plots, but this group of organisms may indicate partially anaerobic soil conditions, rather than beneficial biological activity (Elaine Ingham, pers. commun.).

Table 9. Soil physical and biological properties in low-Ca and high-Ca treatments at Site 1.

	Maximum soil strength (psi) at 0-12 inches			Mean soil strength (psi) at 12-24 inches		Water infiltration rate (min./inch)		
	fall 1999	spring 2000	fall 2000	spring 2000	fall 2000	fall 1999	spring 2000	fall 2000[a]
Low-Ca	490	490	410	210	210	2.9	2.4	14.4
High-Ca	510	500	480	220	270	4.2	2.3	19.2

	Active bacteria, ppm dry soil	Active fungi, ppm dry soil	Mycorrhizal root colonization, %	Ciliate protozoa individuals/gram soil
Low-Ca	27.3	48.2	19	900
High-Ca	14.3	32.6	11	6,400

---

[a] measured at 6 inch depth (hard layer)

Other researchers have warned that gypsum can aggressively leach Mg and K from sandy, low-CEC soils, causing crop deficiencies (Syen-Omar & Sumner, 1991). A modified Albrecht formula (60% Ca, 20% Mg, and 6-10% K) has been recommended for these soils (Kinsey & Walters, 1993, Norman Jones, pers. commun.). In 1999, tomato tended to yield less in the high-Ca plots, but this was not seen with broccoli in the 2000 season (Figure 2). Although some of the differences observed at Site 1 may be artifacts of random variation, the simultaneous occurrence of *several* adverse trends suggests that the base saturation ratio in the low-Ca treatment (Table 2) may be closer to the optimum for this Tidewater sandy loam.

The nature of the hardpan was explored at this location. Soil bulk density at 6-10 inches and at 12-16 inches was about 1.7 regardless of Ca treatment. This is considered high enough to restrict plant roots (USDA, 1999), and only a few thickened, crooked plant roots were observed at depths greater than 8 inches. A soil test at 12-18 inches showed that gypsum treatment had enhanced Ca levels only slightly at this depth. The test also indicated subsoil acidity (pH 5.6) but this is not severe enough to cause aluminum toxicity or Ca deficiency (Sumner, 1993).

Hard layers were found at about 6 inch depth in all fields at the farm, but were absent in an adjacent mature (>50 years) hardwood forest. The grower noted that the previous owners had farmed conventionally with heavy equipment. The county extension agent stated that many of the region's sandy soils have a subsurface "E" (leached) horizon that is particularly susceptible to compaction by heavy traffic. Although the hard layer did not show the light color typical of leached horizons, the soil below 12 inches was distinctly reddish, indication deposition of clays. Despite its high bulk density, the reddish horizon showed very low resistance (100-250 psi).

It was concluded that this hardpan is related to past history of heavy machinery, not to insufficient soil Ca. Chisel plowing, followed by deep-rooted cover crops were recommended.

The finer-textured soil at Site 2 may be responding favorably to gypsum, with slightly reduced hardpan strength and topsoil bulk density (Table 10). Water infiltration was also faster in the high-Ca plots in 2000. Bulk density of the hard layer itself (6-10 inches) did not show the same trend. Where the soil had been loosened to a 14-inch depth with a heavy-duty broadfork (analogous to chisel-plowing) three months prior to measurement, soil strength became low enough to allow deeper root penetration, especially in the high-Ca treatment (Table 10).

Active fungi and bacteria were higher in the high-Ca treatment in March, although field measurements of soil respiration in May and September showed no treatment effect. Protozoan populations show a possible adverse trend (fewer amoebae and more ciliates) with the high-Ca treatment, but this may be confounded by the extreme variability in protozoan counts. Broccoli yields were about 11% higher in the gypsum-treated plots in the 2000 season.

It is interesting to note that this soil had a higher initial K saturation level than the other loamy and clayey soils (Sites 3,4,5). The principal investigator initiated the current research after experiencing tilth problems on a clay-loam with excessive K, and achieving some improvement with high-Ca limestone. Similarly, using a low-K mulch at Site 2 seems to have lowered both soil K and soil strength (Table 8). These trends need to be followed for a few more years to determine whether the gypsum is actually improving soil health.

Table 10. Soil properties in low-Ca and high-Ca treatments at Site 2.

	--Maximum soil strength-- (psi) at 0-12 inches				-----Dry bulk density----- 0-4 inch depth			6-10 in	Water infiltration rate (min./inch)		
	fall 1999	spr. 2000	fall 2000	fall 2000[a]	fall 1999	spr. 2000	fall 2000	fall 2000	fall 1999	spr. 2000	fall 2000[a]
Low-Ca	400	460	430	290	1.09	1.22	1.24	1.59	8.6	2.6	4.4
High-Ca	370	410	370	260	1.08	1.20	1.19	1.63	11.2	1.4	2.1

	Act. bacteria, ppm dry soil	Act. fungi, ppm dry soil	Amoebae, 1,000s./gram soil	Ciliate protozoa indiv. / gram soil
Low-Ca	16.4	12.7	812	900

High-Ca	27.0	27.4	219	3,200

---

[a] measured in crop row that was broadforked in June.

Sites 3 and 4 are both located on creek-bottom loams in the Appalachian region of southwest Virginia. Despite high initial Mg levels, both soils show excellent tilth regardless of Ca treatment. No hardpan exists within the top 24 inches, topsoil bulk density averages 1.0-1.1 (indicating 55-60% pore space), moisture-holding capacity exceeds 4 inches in the top foot of soil, and water infiltration is quite rapid. At Site 4, the mild, moist 2000 season promoted intense earthworm activity (over 30 worms per square foot in the top six inches), which further enhanced soil structure (see Plate 4 in Addenda). Bulk density at the 6-10 inch depth was only 1.2-1.3, and many earthworm channels were observed at this level. There were no significant differences between low-Ca and high-Ca plots in soil physical or biological properties. Thus the high-Mg levels do not appear to have compromised the overall high quality of these soils.

At Site 4, broccoli foliar nutrient levels suggested that the crop absorbed ample N, P, K, Ca and Mg in both treatments. However, tomato showed very high foliar Mg, which was reduced somewhat by the high-Ca treatment (Table 6). Broccoli, tomato and butternut squash all tended to yield better on the Ca-amended plots (Figure 1). This suggests that, when soil Mg reaches 28% saturation, Ca amendments may benefit vegetable crop nutrition, even if soil tilth has not been affected. However, data from additional seasons would be required to confirm these trends.

Site 5 showed the poorest tilth, with severe hardpan beginning at a 4 inch depth, and poor drainage after heavy rains. Although Ca applications have brought cation balance much closer to the Albrecht formula (Table 2), they have thus far had no effect on soil physical properties. The hardpan may be related to a long history of conventional farming with heavy machinery and inadequate organic matter inputs. The field was converted to organic management only in 1996, and the surface few inches of soil already show enhanced organic matter and earthworm activity. Improvements at greater depth may require several more years to develop.

Conclusions

Findings to date do not support the application of a single formula for optimum base saturation ratio to all soils. Instead, a *site-specific* and *resource-conserving* approach to soil cation balancing may better serve the overall goal of sound nutrient management. Furthermore, base saturation ratio is just one component of soil quality, which may be more dramatically enhanced by improving the health and diversity of the soil life. Mineral amendments or other measures to adjust soil cation balance may confer some of the following benefits on *some but not all* soils that depart from the Albrecht formula:

- improved tilth, reduced hardpan, especially on loam or clay with very high K levels
- higher marketable yields in brassicas and other crops with a high Ca requirement

Limited data gathered on foliar nutrient levels, produce quality, and weed, pest and disease pressures, did not support any of the following claims for cation nutrient balancing:

- increased availability and crop uptake of N, P or micronutrients

- increased crop resistance to pests, diseases and environmental stresses
- fewer weeds
- higher soluble solids (Brix)
- longer shelf life

Ca amendments had no apparent effect on soil biological activity level (respiration) or humus formation (active organic matter). However, because of the great complexity of the soil's web of life, and the potentially long time needed for such effects to become manifest, the following claims cannot be fairly evaluated based on data collected thus far:

- stimulation of beneficial soil life and humus formation
- more balanced and diverse soil life, fewer root pathogens

In general, there appears to be little evidence that moderately high Mg levels (20-25% base saturation), and moderately low Ca levels (55-65% base saturation), are harmful to soil or crop health on most soils in the southeastern US. If Mg is high, it makes sense to choose high-Ca lime *if the soil's pH merits liming;* conversely, dolomitic lime should be used on an acid soil with low Mg (<60 ppm or <8% base saturation). However, using lime to "correct" the base saturation ratio of a nearly-neutral soil may be counterproductive, as overliming can tie up micronutrients and possibly inhibit soil life.

Gypsum applications may be appropriate on soils that are low in both Ca and S. However, we found extremely high foliar S in broccoli planted after gypsum was applied at just 500 lb/acre. Possible effects of such high S on the crop are not fully known.

Either lime or gypsum may correct the Ca deficiency and aluminum excess of a highly-acid subsoil (pH <5.0) that restricts crop root growth. However, gypsum can cause excessive leaching losses of K and Mg from sandy soils, and must be used with caution on these soils.

There is some evidence that excessive soil K (>350 ppm, or >8% base saturation on a loam or clay soil) can upset plant nutrition and contribute to a deterioration in crumb structure and tilth. High soil K levels are fairly common in intensive vegetable production, both conventional and organic. In this case, cation balancing measures consist primarily in *reducing* inputs, particularly K-rich materials such as manure, hay mulch and NPK fertilizers.

Other considerations include the economic and environmental costs of amendment applications to "correct" the soil's base saturation ratio. Apparently, about one to two tons per acre of either high-Ca lime or gypsum must be applied to shift the soil's base saturation ratio by 5 to 10 percentage points (a typical goal on a moderately "out-of-balance" soil). This may cost anywhere from $40 to 300 pr acre, including shipping and application. If high-value vegetable crops with a high calcium requirement are grown, this investment may pay off on some soils. For example, a 10% yield increase in broccoli might fetch an extra $150 per acre if the broccoli is wholesaled at $0.50/lb. This would pay for the amendment application in a year or two. However, growers should try this strategy on a small area to verify benefits before applying it to the entire farm. Treating large acreages of hay or agronomic crops with lime or gypsum simply to adjust base saturation ratio may not be good economics. It would also entail significant environmental costs in the mining, transport and application of the materials.

Outreach

During the 2000 season, we held three on-farm field days featuring the ongoing experiments, and a presentation on *Common Sense Soil Nutrient Balancing.* These took place at Site 1 (May 27), Site 4 (June 17) and Site 5 (September 28). The first two were sponsored by the Ecological Production Pledge program of the Virginia Association for Biological Farming (VABF), and the last was sponsored by Rural Resources, an education and advocacy organization for small scale sustainable farming and rural development. About 15 gardeners and farmers attended each event. Two field days were also held in 1998 and one in 1999.

The principal investigator gave presentations on the subject at the Virginia Biological Farming Conference on March 3-4, 2000 (attendance *ca*. 40), and at the Carolina Farm Stewardship Association conference on November 3-5, 2000 (attendance 12). Based on experience with these workshops, a shorter, more grower-friendly presentation with more time for open discussion, will be offered at the Southern Sustainable Agriculture Working Group (SAWG) conference on January 19-21, 2001, and again at the Virginia Biological Farming Conference on February 9-10, 2001.

Participants in the case studies have implemented recommendations, including: (a) gypsum and borax applications to remedy low Ca and B levels (Site 2); (b) switching from hay mulch to leaf mulch and reducing manure compost inputs to lower excessive soil K levels (Potomac Vegetable Farms); and (c) planting heavy K feeders to reduce excessive soil K (Site 3). Annual soil tests have confirmed improved nutrient balance in some of the case study fields.

Project progress reports were published in *The Virginia Biological Farmer* in February and again August 2000 (copies attached). An excerpt of the February 2000 article was reprinted in *Southern Sustainable Farming,* the newsletter of Southern SAWG. The revised information sheets will also be made available through VABF and at regional sustainable agriculture conferences during winter of 2000-2001.

Plans for Future Work

All of the results from this three-year study must be considered preliminary. More data from an additional two to three seasons on these same plots are needed to verify the tentative conclusions presented above, and to fine-tune guidelines for site-specific cation nutrient management. In particular, only limited data were collected on crop quality (Brix, shelf life), and weed, pest and disease levels. Since nutrient balance is known to affect these parameters, further observations in relation to soil cation balance may be warranted. Furthermore, subtle long-term effects of altering base saturation ratio on soil physical and biological properties may require longer than three years to become manifest.

Additional funding will be sought from the Southern Region USDA Sustainable Agriculture Research and Education (SARE) program to continue the field trials through the 2003 season. Potential benefits of preventing or reducing excessive soil K levels in intensive vegetable production will also be explored. If this or other grant proposals are successful, three final reports will be published at the conclusion of the project: a technical report to be submitted to the *American Journal for Alternative Agriculture* or another professional journal; a final version of the information sheet giving guidelines for soil cation balancing; and a 10-15 page project summary, written in farmer-friendly language and made available through VABF and Southern SAWG.

References

A&L Agricultural Laboratories, undated. Soil and Plant Analysis Agronomy Handbook. 132 pp.

Albrecht, W.A., edited by Charles Walters, Jr., 1975. *The Albrecht Papers, Volume 2, Soil Fertility and Animal Health.* Acres USA, Kansas City, MO. 192 pp.

Albrecht, W.A., edited by Charles Walters, Jr., 1989. *The Albrecht Papers, Volume 3, Hidden Lessons in Unopened Books.* Acres USA, Kansas City, MO. 401 pp.

Allaway, W.H., 1945. *Availability of replaceable calcium from different types of colooids as affected by degree of calcium saturation.* Soil Sci. 59: 207-217.

Bar-Tel, A. & E. Pressman, 1996. *Root restriction and potassium and calcium solution concentrations affect dry matter production, cation uptake and blossom-end rot in greenhouse tomato.* J. Amer. Soc. Hort. Sci. 121(4):649-655.

Baver, L.D., W.H. Gardner & W.R. Gardner, 1972. *Soil Physics.* John Wiley & Sons. 498 pp.

Bear, F.E. & S.J. Toth, 1948. *Influence of calcium on availability of other soil cations.* Soil Sci. 65:69-74

Brady, N.C. & R.R. Weil, 1999. *The Nature and Property of Soils.* 12th edition. Prentice Hall, Upper Saddle River, NJ. 881 pp.

Cantisano, A., 1992. *Know Your Soil: a handbook for understanding your soil report.* Organic Agricultural Advisors, Colfax, CA. 15 pp.

Curtin, D., H. Steppultin & F. Selles, 1994. *Effects of Mg on cation selectivity and structural stability of sodic soils.* Soil Sci. Soc. Amer. J. 58:730-737.

Diver, Steve, 1995. *Albrecht/Reams Biological Fertility Systems.* Appropriate Technology Transfer for Rural Areas. Includes a 13-page bibliography.

Eckert, D.J., 1987. *Soil test interpretations: basic cation saturation ratios and sufficiency levels.* Pp. 53-64 in Soil Science Soc. Amer. Special Publ. 21, Soil Testing, Sampling, Correlation, Calibration and Interpretation.

Forster, R.L. & E. Echandi, 1975. *Influence of calcium nutrition on bacterial canker of resistant and susceptible Lycopersicon spp.* Phytopathology 65: 84-85.

Geraldson, C.M., 1954. *The control of blackheart of celery.* Proc. Amer. Soc. Hort. Sci. 63: 353-358.

Goldstein, W., 1990. *Cation Balancing: is it Beneficial or Bogus?* 6 pp. Available from Michael Fields Agricultural Institute, 3293 Main St., East Troy, WI.

Greene, R.S.B. & G.W. Ford, 1985. *The effect of gypsum on cation exchange in two red duplex soils.* Aust. J. Soil Res. 23:61-74.

Grierson, I.T., 1978. *Gypsum and the red brown earths.* Chapter 42 (pp 315-324) in W.W. Emerson, R.D. Bond & A. R. Dexter, eds., *Modification of Soil Structure*, 438 pp.

Ingham, Elaine, 1999. *The Soil and Foliar Foodweb.* Oral presentation at the Southern Region SARE PDP Soil Management Train-the-Trainer Workshop, Sept. 21-24, 1999, Raleigh, NC.

Ingham, Elaine. Soil micro-ecologist, Soil Foodweb Inc., Corvallis, OR. Personal communication, 1998-99.

Islam, K.R. & R.R. Weil, 2000. *Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management.* J. Soil & Water Conserv 55(1st. Qtr. 2000): 69-78.

Jones, Norman, 1998. Soil scientist, A&L Eastern Agricultural Laboratories, Inc, Richmond, VA. Personal communication.

Key, J.L., L.T. Kurtz & B.B. Tucker, 1962. *Influence of ratio of exchangeable Ca:Mg on yield and composition of soybeans and corn.* Soil Sci 93: 265-270.

Kinsey, Neal & Charles Walters, 1993. *Neal Kinsey's Hands-On Agronomy.* Acres USA, Kansas City, MO. 352 pp.

Kirkby, E.A., 1979. *Maximizing calcium uptake by plants.* Commun. Soil Sci. Plant Anal. 10(1-2):89-113.

Liebhardt, W.C., 1981. *The basic cation saturation ratio concept and lime and potassium recommendations on Delaware's coastal plain soils.* Soil Sci. Soc. Amer. J. 45:544-549.

Luebben, Carl, 1995. Agricultural consultant in Virginia; personal communication.

Martin, J.P. & A.L. Page, 1969. *Influence of exchangeable calcium and magnesium and of percentage base saturation on growth of citrus plants.* Soil Sci. 107:39-46.

Magdoff, F. & H. van Es, 2000. Building Soils for Better Crops. Sustainable Agriculture Publications, Hills Building, Room 10, University of Vermont, Burlington, VT 05405-0082.

Maynard, D.N., B. Gersten, R.E. Young & H.F. Verneli, 1963. *The influence of plant maturity and calcium level on the occurence of carrot cavity spot.* Proc. Amer. Soc. Hort. Sci. 83:506-510.

MeLean, E.O., 1972. *Base saturation ratio versus insufficiency-sufficiency values as bases for fertilizing and liming of soils.* Commun. Soil Sci. Plant Anal. 3(2):141-149.

McLean, E.O., 1977. *Contrasting concepts in soil test interpretation: sufficiency levels of available nutrients versus base cation saturation ratios.* Amer. Soc. Agro. Spec. Publ. No. 29, pp 39-54.

Mehlich, A., 1942. *The significance of percentage base saturation and pH in relation to soil differences.* Soil Sci. Soc. Amer. Proc. 7: 167-174.

Mehlich, A., 1946. *Soil properties affecting the proportionate amounts of calcium, magnesium and potassium in plants and in HCl extracts.* Soil Sci. 62: 393-409.

Mehlich, A. & W.E. Colwell, 1943. *Influence of nature of soil colloids and degree of base saturation on growth and nutrient uptake by cotton and soybeans*. Soil Sci. Soc. Amer. Proc. 8: 179-184.

Phelan, P.L., 1997. *Soil-management history and the role of plant mineral balance as a determinant of maize susceptibility to the European corn borer*. Entomological Research in Organic Agriculture, pp 25-34.

Putney, Reid, 1998. Agricultural consultant in Virginia; personal communcation.

Schonbeck, M.W., 2000. *Soil Nutrient Balancing in Sustainable Vegetable Production.* Progress report to Organic Farming Research Program, January 2000.

Simson, C.R., R.B. Corey & M.E. Sumner, 1979. *Effect of varying Ca:Mg ratios on yield and composition of corn (Zea mays) and alfalfa (Medicago sativa)* Commun. Soil Sci. Plant Anal. 10(1-2): 153-162.

Sumner, M.E., 1993. *Gypsum and acid soils: the world scene.* Adv. Agronomy 51:1-32.

Syen-Omar, S.R. & M.E. Sumner, 1991. *Effect of gupsum on soil potassium and magnesium status and growth of alfalfa.* Commun. Soil Sci. Plant Anal. 22: 2017-2028.

United States Department of Agriculture, 1999. *Soil Quality Test Kit Guide*. 82 pp.

Volpin, H. & Y. Elad, 1991. *Influence of calcium nutrition on susceptibility of rose flowers to Botrytis blight*. Phytopathology 81: 1390-1394.

Weil, Raymond, 1999. Professor of soil science, University of Maryland; personal communication.

Yamazaki, H. & T. Hoshina, 1995. *Calcium nutrition affects resistance of tomato seedlings to bacterial wilt.* HortScience 30(1): 91-93.

Young, Gregg A., 1999. *A Training Manual for Soil Analysis Interpretation in Northern California.* Master's Thesis, Sonoma State University. 158 pp. Available through Y&B Agricultural Services, P.O. Box 246, Talmage, CA 95481; tel. 707-485-5121.

Zimmer, Gary, 1999. *Biological Farming*. Oral presentation at the 1999 ACRES USA Eco-Farming Conference.

Addenda to the Final Report

Three information sheets revised and published in December 2000:

How to Use a Soil Test (2 pp)
Soil Cation Nutrient Balancing – Missing Link or Red Herring? (4 pp)
Does My Soil Need Cation Nutrient Balancing? (4 pp)

Progress Report, February 2000 issue of Virginia Biological Farmer (4 pp)
Progress report, Aug-Sept 2000 issue of Virginia Biological Farmer (1 p)

Annotated bibliography on soil nutrient balancing, and supplement to the bibliography (13 pp)

Photographs of study sites, showing methods of field measurements, and field days (4 pp):

Plate 1. Field Day at Dayspring Farm in Cologne, VA (Site 1) on May 27, 2000, (Site 1). *Left:* about fifteen people attend the tour. *Right:* Mark Schonbeck discusses the use of a heavy-duty broadfork (or chisel plow at the farm scale), and deep-rooted crops to relieve a hardpan that has not responded to cation nutrient balancing alone.

Plate 2. Monitoring soil conditions in the field at Site 1. *Left:* a 5-inch diameter single-ring infiltrometer is used to measure rate of water infiltration into the hard layer (6-inch depth). *Right:* a 3-inch diameter soil core is taken at a 12-16 inch depth to determine bulk density of the subsoil. Plant roots become scarce below 6 inches.

Plate 3. Monitoring soil conditions in the field. *Top:* a 5-inch diameter ring is carefully inserted into the soil surface and covered with an airtight lid equipped with septum stoppers to measure soil respiration (Site 5). After an incubation of 1 to 2 hours, an air sample is drawn from the enclosure through a Draeger™ indicator tube to measure carbon dioxide accumulation. *Bottom:* at Site 4, a 1-foot square quadrat is excavated to a 6-inch depth to estimate earthworm populations within the topsoil.

Plate 4. The soil at Site 4 shows excellent tilth despite high Mg (28% base saturation). *Left:* Good crumb structure, enhanced by earthworm activity. Most of the aggregates (crumbs) visible at the surface are worm castings. *Right:* Measuring bulk density at the 6-10 inch depth. Numerous deep earthworm burrows (at least 6 visible within the ring) promote rapid water infiltration and reduce bulk density.