Published online March 12, 2007

A Review of the Use of the Basic Cation Saturation Ratio and the "Ideal" Soil

Peter M. Kopittke*
Neal W. Menzies
School of Land and Food Sciences
The Univ. of Queensland
St. Lucia, Qld
Australia 4072

The use of "balanced" Ca, Mg, and K ratios, as prescribed by the basic cation saturation ratio (BCSR) concept, is still used by some private soil-testing laboratories for the interpretation of soil analytical data. This review examines the suitability of the BCSR concept as a method for the interpretation of soil analytical data. According to the BCSR concept, maximum plant growth will be achieved only when the soil's exchangeable Ca, Mg, and K concentrations are approximately 65% Ca, 10% Mg, and 5% K (termed the *ideal soil*). This "ideal soil" was originally proposed by Firman Bear and coworkers in New Jersey during the 1940s as a method of reducing luxury K uptake by alfalfa (*Medicago sativa* L.). At about the same time, William Albrecht, working in Missouri, concluded through his own investigations that plants require a soil with a high Ca saturation for optimal growth. While it now appears that several of Albrecht's experiments were fundamentally flawed, the BCSR ("balanced soil") concept has been widely promoted, suggesting that the prescribed cationic ratios provide optimum chemical, physical, and biological soil properties. Our examination of data from numerous studies (particularly those of Albrecht and Bear themselves) would suggest that, within the ranges commonly found in soils, the chemical, physical, and biological fertility of a soil is generally not influenced by the ratios of Ca, Mg, and K. The data do not support the claims of the BCSR, and continued promotion of the BCSR will result in the inefficient use of resources in agriculture and horticulture.

Abbreviations: BCSR, basic cation saturation ratio; CEC, cation exchange capacity.

The aim of most soil analytical tests is to provide a measure of the phytoavailability of a nutrient—either measured as nutrient intensity (instantly available), quantity (total amount available), or buffering capacity (the rate of change in quantity with respect to intensity). The information gathered from soil testing is often used to guide fertilization practices. Of particular interest to this review are the cations Ca^{2+}, Mg^{2+}, and K^{+}, which, in a typical soil, are present in the solution phase (intensity), but are predominantly adsorbed on the soil's exchange complex (quantity). While it is typically comparatively easy to measure the soil's exchangeable cations, it is more difficult to relate the analytical data obtained to phytoavailability and plant growth. Soil concentrations of Ca, Mg, and K are generally interpreted using two different methods—the sufficiency level of available nutrients (SLAN) concept and the BCSR concept (Haby et al., 1990; McLean, 1977).

According to the sufficiency level concept, there are definable levels of individual nutrients in the soil below which crops will respond to added fertilizers and above which they will probably not respond (Eckert, 1987). Thus, once the nutrient is present in sufficient quantity, plant growth will be maximal across a range of nutrient concentrations before eventually decreasing as toxic levels are reached. Often, the main objective when using the sufficiency level concept is to fertilize according to the plant's needs (Eckert, 1987). Although the critical deficiency concentrations for exchangeable Ca, Mg, and K vary for each individual plant species, they have been reported to be in the range of 0.5 to 1.5 $cmol_c\ kg^{-1}$ for Ca, 0.2 to 0.3 $cmol_c\ kg^{-1}$ for Mg, and 0.2 to 0.5 $cmol_c\ kg^{-1}$ for K (Aitken and Scott, 1999; Bruce, 1999; Gourley, 1999).

In contrast to the sufficiency level concept, the BCSR (also known as "mineral balancing") aims to fertilize according to the soil's needs (Eckert, 1987). The BCSR holds that there is a balanced ratio of basic cations (Ca^{2+}, Mg^{2+}, and K^{+}) for the soil's cation exchange capacity (CEC), and that plant growth will be reduced in soils that do not contain the cations in the specified ratio (McLean, 1977). This idea originated largely from the work of Bear and coworkers in New Jersey, who proposed the concept of a soil that they considered was "ideal": "the absolute amounts of available Ca, K, and Mg are not so important as their relative values" (Bear et al., 1951). This "ideal soil" proposed by Bear was widely promoted by William Albrecht as a "balanced soil," particularly through publications such as *The Albrecht Papers* (Albrecht, 1975). Albrecht was Professor of Soils and Chairman of the Department of Soils at the University of Missouri (College of Agriculture), and made an outstanding contribution to soil science during a long period of time. While various values have been proposed for the BCSR, they generally fall within the following approximate range (saturation percentage of the CEC): 65 to 85% Ca, 6 to 12% Mg, and 2 to 5% K (values proposed by Graham, 1959).

While university laboratories almost exclusively use the sufficiency level concept to interpret soil analytical data (Eckert, 1987), McLean (1977) suggested that approximately 80% of the samples being tested in the north-central region of the USA in the late 1960s were tested in private laboratories and interpreted according to the BCSR concept. Similarly, Liebhardt (1981) estimated that between 80 and 90% of the soils tested in Delaware used the BCSR. It is estimated that at least 90 to 95% of the soils tested by the turf industry in Australia are currently tested according to the

Soil Sci. Soc. Am. J. 71:259–265
doi:10.2136/sssaj2006.0186
Received Received 11 May 2006.
*Corresponding author (p.kopittke@uq.edu.au).

677 S. Segoe Rd. Madison WI 53711 USA

BCSR concept. In a field experiment conducted in Nebraska over a period of 8 yr, the cost of purchasing fertilizer according to the recommendations of the BCSR concept was generally double that of when the fertilizer was purchased based on SLAN recommendations (Olson et al., 1982).

This review examines the suitability of the BCSR concept as a method for the interpretation of soil analytical data. A brief history of the ideal soil concept is provided, and several studies examining plant growth in the ideal soil (particularly those published by the proponents of the BCSR) are summarized in relation to the soil's chemical, physical, and biological fertility. It is hoped that this review will provide useful information on the measurement and interpretation of soil analytical data when making agronomic decisions.

Research before Circa 1930s

It appears that Loew (1892) was the first to suggest that there is an optimal ratio between Ca and Mg. This hypothesis arose from the observation that both lime (Ca) and Mg are toxic to plants when present in a large excess of the other (Loew, 1892). After reviewing the literature and conducting their own investigations, Loew and May (1901) concluded that "the best proportion of soluble lime to soluble magnesia for the germination and growth of plants is about molecular weight 5 to 4." Close examination of their data, however, reveals that, for several of the species examined, maximum growth was obtained across a range of Ca/Mg ratios. Indeed, Loew and May (1901) reported that of the five Ca/Mg treatments for oat (*Avena sativa* L.), growth was normal in all except at the highest Ca/Mg ratio. Nevertheless, their Ca/Mg ratio hypothesis attracted a great deal of attention, and during the next decade it was the subject of much research, particularly in the USA and Japan.

Lipman (1916) reviewed the topic, and found that while several researchers had identified optimal Ca/Mg ratios for various plant species, many were unable to identify a precisely defined ratio that improved growth but rather found that growth was maximal across a range of ratios. Interpreting the results of many of these early studies cited by Lipman is difficult, however, as soil pH was rarely (if ever) controlled. Indeed, the addition of lime to increase the Ca/Mg ratio simultaneously increased soil pH and thereby reduced any growth limitations imposed on the plant by soil acidity (such as Al and Mn toxicity), and may also have reduced P deficiency. Similarly, at high Ca/Mg ratios it was often noted that many of the leaves displayed chlorosis, and that this chlorosis could be alleviated by the addition of Fe to the roots—typical symptoms of lime-induced chlorosis (Schinas and Rowell, 1977). In his review, however, Lipman concluded that that there was no basis to the idea that the Ca/Mg ratio influenced plant growth.

The literature was reviewed again by Moser (1933), who also conducted his own research into Ca/Mg ratios. Moser concluded that there was no correlation between the Ca/Mg ratio and crop yield, but rather, that yield was dependent on the Ca status of the soil. Indeed, in soils with high Mg contents, low yields often resulted from a Ca deficiency rather than an excess of Mg.

Development of the Current "Ideal Soil" Concept

During the 1940s, Bear and coworkers conducted a series of studies at the New Jersey Agricultural Experiment Station investigating the growth of alfalfa. Much of this work was conducted using either the homoionic clay methodologies developed by Albrecht and McCalla (1938), or using 20 of New Jersey's most important agricultural soils in glasshouse pot trials. Bear et al. (1945) tentatively stated that their evidence indicated that, "for the ideal soil, … 65% of the exchange complex should be occupied by Ca, 10% by Mg, 5% by K, and 20% by H." Thus, according to Bear and Toth (1948) this composition for an ideal soil suggests a Ca/Mg ratio of 6.5:1, a Ca/K ratio of 13:1, a Ca/H ratio of 3.25:1, and a Mg/K ratio of 2:1 (all ratios are presented on a charge [equivalent] basis). It is unclear, however, how these values for the ideal soil were established. These tentative results concerning the ideal soil were confirmed by Bear and Toth (1948).

Since the publication of these reports by Bear, it has been assumed by many that optimum plant growth will *only* occur when these ideal conditions are met. This is despite Bear and coworkers' acknowledgment that maximum growth will occur across a wide variety of cation ratios. In their work, the purpose of providing a high Ca saturation (65%) was to allow maximum growth while also minimizing luxury K uptake. Indeed, Bear and coworkers note that: (i) good growth occurs across a wide range of Ca/K ratios (see below), (ii) a high Ca saturation percentage limits luxury K uptake, and (iii) "K is a much more expensive element than the Ca which it replaces" (Bear and Toth, 1948). Thus, the application of Ca to reduce K uptake was cheaper than applying K that would be taken up by the plant in luxurious amounts. Although split K applications was considered as a method for reducing luxury K uptake (Bear and Toth, 1948), it appears that this practice was never explored in detail.

After the publication of the ideal soil by Bear and coworkers, Graham (1959), who was a colleague of Albrecht at the University of Missouri Agricultural Experiment Station, refined the composition of the ideal soil. He stated that "the balance soil scientists recommend… is 75% Ca, 10% Mg and from 2.5 to 5% K." In addition, he also suggested that the range could be from 65 to 85% for Ca, 6 to 12% for Mg, and 2 to 5% for K. Although it is unclear from this 1959 publication how Graham concluded that these values were "balanced," Liebhardt (1981) reported that these "balanced" values had resulted from the modification of the data of Bear et al. (1945), Bear and Toth (1948), and Hissink (1925) to suit the conditions in Missouri.

At about the same time that Bear was conducting his investigations, Albrecht and coworkers were also conducting a series of experiments at the Missouri Agricultural Experiment Station. Much of their research investigated the growth (and N_2 fixation) of legumes, and examined the effect of soil fertility on plant palatability and the nutrition of grazing animals. In many of these studies, clay minerals were extracted from the soil, subjected to electrodialysis, then saturated with various cations such as Ca, K, Mg, and Ba (see Albrecht and McCalla, 1938). By mixing these clays at different ratios, Albrecht was able to investigate the effect of cation saturation on plant growth.

Albrecht concluded that it is important to maintain a high Ca saturation percentage. Indeed, it was this observation that would eventually form the basis for much of Albrecht's concept of the "balanced soil." It would seem, however, that the design and interpretation of the experiments used to demonstrate the need for a high Ca saturation were often flawed. Based on experiments with soybean [*Glycine max* (L.) Merr.], Albrecht (1937) concluded that (i) the nodulation of legumes in acidic soils is limited by low Ca concentrations more than by the acidity itself, and (ii) plant growth and nodulation increase as Ca saturation increases. In fact, Albrecht later stated that "plants are not sensitive to, or limited by, a particular pH value of the soil" (Albrecht, 1975) and that "nitrogen fixation is related to acidity, or pH, only as this represents a decreasing supply of Ca as a plant nutrient" (Albrecht, 1939). Examination of the data of Albrecht (1937), however, reveals that nodulation is indeed inhibited by soil acidity; nodulation only occurred when the pH was ≥5.5, and no nodulation occurred at pH 4.0, 4.5, or 5.0 at any Ca concentration (Fig. 1). Similarly, although Albrecht concluded that growth and nodulation improve as Ca saturation percentage increases, soil pH values were not reported for any treatment, and due to the methodology used, any increase in Ca saturation would have undoubtedly been confounded by a decrease in acidity. Indeed, the various Ca saturations were achieved by mixing H-saturated clay (pH 3.6) (Albrecht, 1939; Albrecht and McCalla, 1938) with Ca-saturated clay (~pH 7.0) (Albrecht, 1939; Hutchings, 1936), thus giving clays of varying acidity (Albrecht, 1939). Using the same experimental system, Hutchings (1936) (who was working with Albrecht in Missouri) reported that a treatment containing 0% Ca clay (100% H clay) had a pH of 3.5, 25% Ca clay a pH of 4.3, 50% Ca clay a pH of 5.0, 75% Ca clay a pH of 5.7, and 100% Ca clay a pH of 6.9. In another experiment conducted by Albrecht (1937), Ca-saturated clay was mixed with Ba-saturated clay. Here, the poor growth observed at low Ca saturation (high Ba saturation) was probably due to (i) Ba toxicity (Ba is phytotoxic at <500 μ*M* [Llugany et al., 2000; Watanabe and Okada, 2005]), or (ii) S deficiency, due to the very low solubility of $BaSO_4$ (Budavari, 1989). Albrecht's idea that plant growth is not limited by acidic conditions per se was explored again by Harston and Albrecht (1942). Also using soybean, they concluded that since the soil pH at the beginning of the experiment (>7.0) was up to two units higher than that at the end of the experiment, plants must be able to tolerate changes in pH, and hence soil acidity is not directly toxic to plants.

According to *The Albrecht Papers* (Albrecht, 1975), Albrecht (1939) demonstrated that for a balanced soil, "65% of that clay's capacity (needs to be) loaded with Ca, 15% with Mg." It is unclear, however, how these "balanced" percentages were derived, as examination reveals that the rate of N_2 fixation (measured as the difference in N content between the plant and the seed) increased linearly with Ca saturation—the greatest fixation actually occurring at the highest rate of Ca saturation, i.e., 88% (vs. the "balanced" Ca saturation of 65%; Fig. 2). Similarly, the work of Albrecht (1937) showed that both plant mass and nodulation rate increased linearly with increasing Ca saturation. Later, and notably after the work of Bear and Graham had been published, Albrecht stated that "extensive research projects served up this working code for balanced plant nutrition: H, 10%; Ca, 60 to 75%; Mg, 10 to 20%; K, 2 to 5%; Na, 0.5 to 5.0%; and other cations, 5%" (Albrecht, 1975). While it is unclear as to the exact origin of Albrecht's "balanced soil," it appears likely that it relied, at least to some extent, on the "ideal soil" of Bear and coworkers.

Whatever the exact origin and original purpose of the ideal soil, the BCSR concept has subsequently been promoted widely, and many now consider that optimal plant growth will only occur when the soil contains the balanced (or ideal) cation ratios (i.e., the BCSR). The remainder of this review will examine the chemical, physical, and biological properties of "balanced" and "unbalanced" soils.

Soil Chemical Properties

According to the BCSR concept, a "balanced soil" (and the Ca/Mg, Ca/K, and Mg/K ratios therein implied) is required to ensure that plants produce both maximum quantity (yield) and quality. Thus, plants grown in a soil whose exchange complex is not "balanced," i.e., does not contain the specified cation ratios, may have reduced yield. Furthermore, animals consuming plants grown on such soils may have reduced weight gain or suffer nutrient imbalances (such as hypomagnesaemia [grass tetany]) due to the reduced quality of the plants. The effect of the "balanced soil" (and cation ratios) on plant yield will be considered first.

Toth, who had worked with Bear in the 1940s during the conception of the ideal soil approach, conducted an experiment investigating the growth of ladino clover (*Trifolium repens* L.;

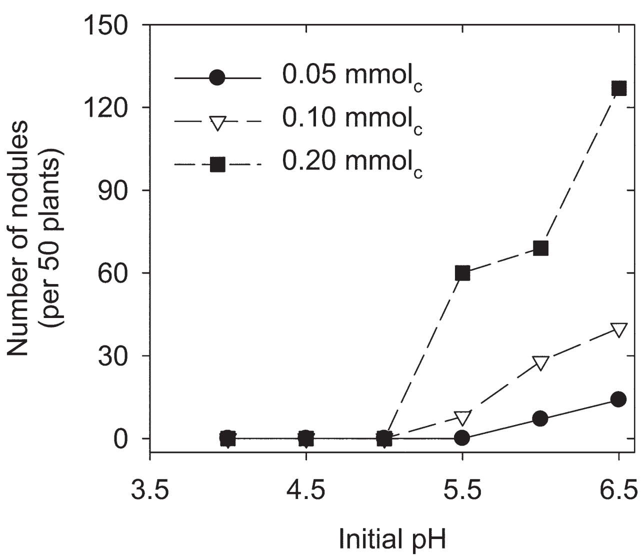

Fig. 1. Effect of initial soil pH on the nodulation of soybean. Calcium was supplied at three levels: 0.05, 0.10, or 0.20 mmol$_c$ Ca per plant. Data taken from Albrecht (1937).

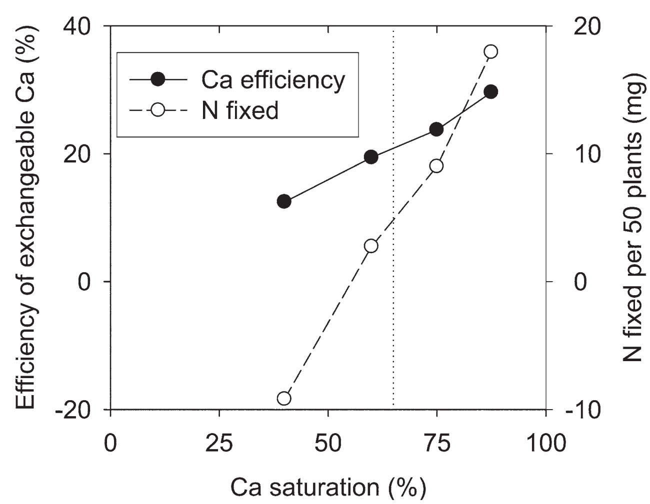

Fig. 2. Nitrogen fixation (measured as the difference between final plant N content and initial seed N content) as related to the efficiency of Ca use (the percentage of the Ca supplied that was taken up by the plants) at different degrees of Ca saturation of a clay mineral. Data from Albrecht (1939). Vertical dotted line is 65% Ca saturation. Scales on each of the axes presented as in Albrecht (1939).

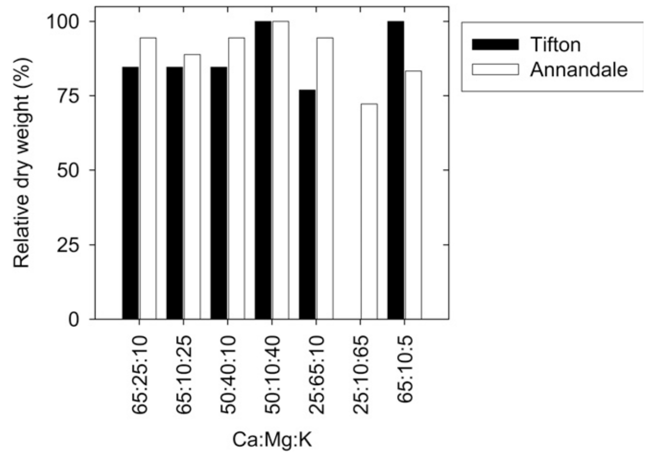

Fig. 3. The effect of the saturation of the soil cation exchange capacity by various amounts of Ca, Mg, and K on the relative yield of ladino clover. Data taken from Giddens and Toth (1951) for two (Tifton and Annandale sandy loams) of the four soils investigated. Data are sorted in order of decreasing Ca saturation. The columns at the far right of the graph (65:10:5) would reflect the "ideal soil" as proposed by Bear et al. (1945). Giddens and Toth (1951) did not present statistical differences.

Giddens and Toth, 1951). Four soils were saturated at seven Ca/Mg/K ratios (with one being "ideal"), and plant growth was compared between treatments. It was concluded that, provided Ca was the dominant cation, no specific cation ratio produced the best yield. Indeed, examination of their results shows that even when the exchange complex contained 40% K or 40% Mg (Fig. 3), growth was no different to that obtained on the "ideal soil," which contained 5% K and 10% Mg.

Specific cation ratios (i.e., Ca/Mg, Ca/K, and K/Mg ratios) were also investigated. McLean, who had worked with Albrecht in Missouri during the 1940s, studied the effect of the soil Ca/Mg ratio on the growth of German millet [*Setaria italica* (L.) P. Beauv. cv. German] and alfalfa (McLean and Carbonell, 1972). It was concluded that plant yields were not affected by the Ca/Mg ratio within the Ca/Mg range studied (2.2:1–14.3:1; Fig. 4). Similarly, Hunter (1949), who had worked with Bear in New Jersey during the early 1940s, investigated the influence of the Ca/Mg ratio on the yield of alfalfa. Even though the experiment covered a wide range of Ca/Mg ratios (0.25:1–31:1), Hunter concluded that there was no "best" Ca/Mg ratio for optimum growth (Fig. 5). Indeed, the Ca/Mg ratios of agricultural soils are seldom found outside of the range investigated by Hunter. Key et al. (1962) investigated the growth of soybean in sand–cation-exchange resin mixtures with a variety of CECs, and with Ca/Mg ratio ranging from 50:1 to 1:50. They concluded that, provided the Ca/Mg ratio was >1 (i.e., Ca > Mg), there was no optimum ratio for plant growth. Liebhardt (1981) also concluded that a wide range of Ca/Mg ratios are able to satisfy the nutrient requirements of maize (*Zea mays* L.) and soybean. Similarly, in field trials conducted in Western Australia during a 6-yr period, variations in the Ca/Mg ratio (0.4:1–17:1) generally did not influence the yield of barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), or lupins (*Lupinus angustifolius* L.) (Western Australian No-Tillage Farmers Association, 2005).

Hunter et al. (1943) investigated the effect of the Ca/K ratio on the growth of alfalfa in a series of soils that had been prepared by mixing sand with various quantities of Ca- and K-saturated homoionic clays. From this study, Hunter et al. (1943) concluded that alfalfa could adjust itself to wide variations in soil Ca/K ratios, making normal growth at ratios anywhere between 1:1 and 100:1 (Fig. 6).

In summarizing their 8 yr of studies, Bear and Toth (1948) stated that the work conducted by Prince et al. (1947) with alfalfa indicated that "the K:Mg ratio was even more important than the Ca:K ratio," and that the "response to Mg additions is governed in part by its ratio to the other cations on the exchange complex, particularly those of Ca and K." In addition, Bear et al. (1951) also

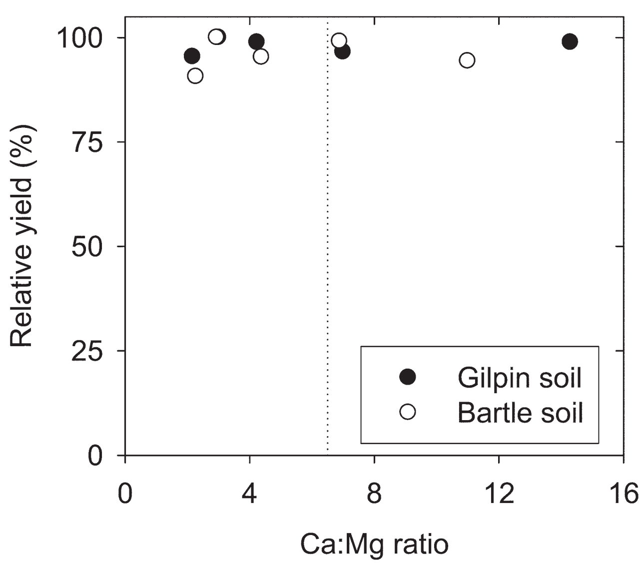

Fig. 4. Effect of the exchangeable Ca/Mg ratio (2.2:1–14:1) on the relative dry matter yield of German millet in two soils. Data taken from McLean and Carbonell (1972). The dotted line indicates the "ideal" Ca/Mg ratio of 6.5:1 as stated by Bear et al. (1945).

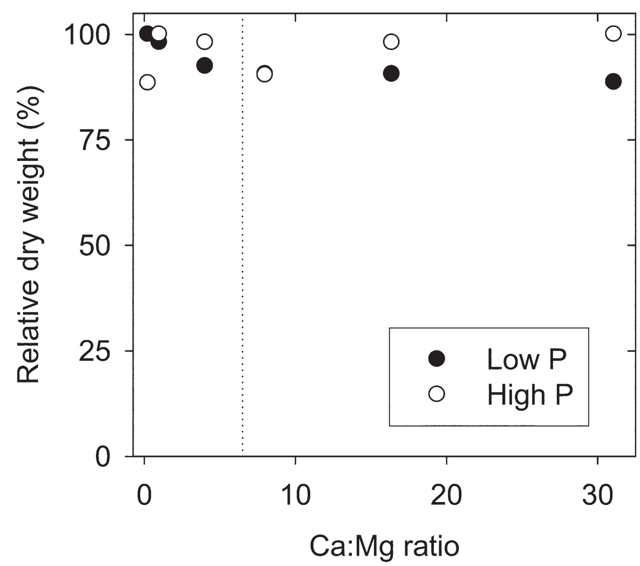

Fig. 5. Effect of the exchangeable Ca/Mg ratio (0.25:1–31:1) on the relative shoot dry weight of alfalfa at two P fertilization levels. Soils were prepared by mixing homoionic clays at various ratios, with K-saturated clays accounting for 10% of the total. Data taken from Hunter (1949). The dotted line indicates the "ideal" Ca/Mg ratio of 6.5:1 as stated by Bear et al. (1945).

stated that Mg deficiencies are likely to develop when the K/Mg ratio >1:2. Indeed, under certain conditions, large applications of K fertilizer cause a reduction in the uptake of Mg (see Haby et al., 1990). The data of Bear et al. (1951) show, however, that the yield of tomato (*Lycopersicon esculentum* Mill.) was not influenced by K/Mg ratio across the range 1:1 to 20:1. Similarly, after studying the growth of sorghum [*Sorghum bicolor* (L.) Moench] in a sand culture system containing a K/Mg ratio up to 7.7:1 (reported as 25:1 on a parts-per-million basis), Ologunde and Sorensen (1982) concluded that, provided the absolute amounts of K and Mg were adequate to meet the demands of the plants, the K/Mg ratio in the growth medium could vary without causing any adverse effect on plant growth.

Thus it would appear that, provided the soil contains adequate absolute quantities of Ca, Mg, and K, the ratios of these cations (Ca/Mg, Ca/K, and K/Mg) generally do not influence plant yield within the ranges commonly found in soils. Therefore, total availability or supply is typically more important.

Besides yield, it has also been considered that under "unbalanced" conditions, plant quality may also be reduced. Indeed, Smith and Albrecht (1942) proposed that crops will be of lower nutritional value when grown on soils that do not contain balanced levels of nutrients. Due to the effect of N_2 fixation on plant protein concentration, much of Albrecht's initial investigations into the effect of the soil on plant quality focused on legumes. As discussed above, it was through this work that Albrecht concluded that acidity per se is not limiting to plant growth, and that soils require a high Ca saturation for optimal growth. Interpretation of much of Albrecht's growth data is confounded by changes in pH, however. Plant growth is limited in acidic soil conditions, and the addition of Ca alone will not overcome the limitations imposed in such soils. Studying soybean in acidic soils ($pH_{1:5}$ 4.6–5.6), Bruce et al. (1988) found that the addition of Ca (by using $CaSO_4$ or $CaCl_2$) without a concurrent increase in pH typically had no effect on plant growth (as measured by root length). In contrast, root length increased significantly when both pH and Ca concentration were simultaneously increased (by the use of $CaCO_3$). Indeed, there is an extensive literature demonstrating the negative effect of acid soils, particularly that caused by toxic levels of Al and Mn (e.g., Foy, 1984). Nodulation of legumes is particularly sensitive to acidic conditions and high Al concentrations (Alva et al., 1987).

In addition to the work investigating the growth and nodulation of legumes, Albrecht also investigated the effect of the soil properties on the health and nutrition of grazing animals. Albrecht found that the addition of soil amendments such as lime and phosphate often increased crop quality (protein, feed-use efficiency, etc.; Albrecht and Smith, 1941; McLean et al., 1943; Smith and Albrecht, 1942). Several aspects of these studies by Albrecht are questionable, however. First, the observed increases in quality often corresponded to an increase in yield, thereby indicating that the reduced quality in the control was probably due to the presence of growth-limiting factors (for example, Table 1 of Albrecht and Smith, 1941). Second, although the addition of soil amendments increased quality, optimum application rates were not determined, and the soil properties (such as the percentage of saturation with Ca, Mg, and K) were not measured. Hence, the reported yield and quality increases cannot be ascribed with certainty to those conditions that were later promoted as "balanced." Finally, although the addition of lime (Ca) to move the soil closer to that considered "balanced" was expected to increase animal productivity through an improvement in plant quality, in some instances, lime application unexpectedly reduced animal live-weight gains (for example, Table 6 of Smith and Albrecht, 1942). Overliming has since been reported to reduce crop yield due to a deterioration of soil structure, reduction in P availability, and induced trace element deficiencies (Kamprath, 1971).

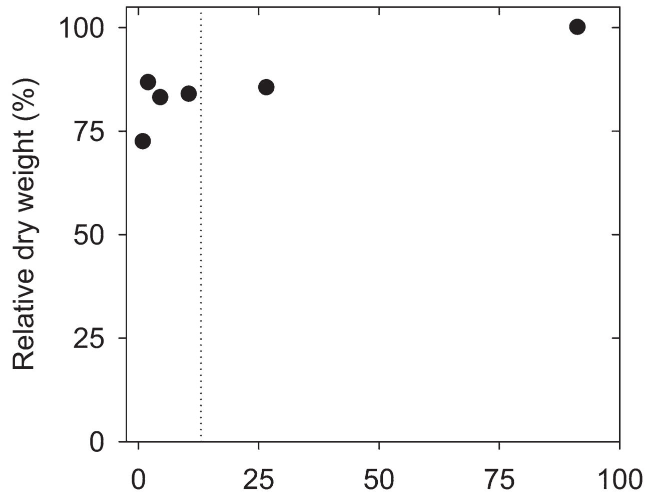

Fig. 6. Effect of the exchangeable Ca/K ratio (1:1–91:1) on the relative dry weight of alfalfa. Soils were prepared by mixing homoionic clays at various ratios. Data taken from Hunter et al. (1943). The dotted line indicates the "ideal" Ca/K ratio of 13:1 as stated by Bear et al. (1945).

Recently, Stevens et al. (2005) studied the growth of cotton (*Gossypium hirsutum* L.) in a range of Missouri soils. They observed that lint yield, micronaire, uniformity, and fiber strength were no better in a soil containing a Ca/Mg ratio of 6.5:1 than in any of the other soils that contained a Ca/Mg ratio ranging from 7.6:1 to 2.5:1 (Table 1). Similarly, investigating vegetable production, Schonbeck (2000) conducted a series of on-farm studies in Virginia, where the

Table 1. Effect of soil chemical properties from a long-term field experiment on average cotton fiber micronaire, uniformity, strength, and lint yields. Table taken from Stevens et al. (2005).

Ca/Mg ratio	pH_{salt}	Cation exchange saturation			Cotton fiber			Lint yield
		Ca	Mg	K	Micronaire	Uniformity	Strength	
		%				%	cN tex^{-1}	kg ha^{-1}
7.6	6.3	76	10	9	4.3	83.6	27.9	897
7.2	6.2	72	10	8	4.3	82.9	28.2	821
7.4	6.4	74	10	9	4.2	83.4	28.2	902
6.3	6.2	69	11	9	4.3	83.9	28.1	842
4.8	6.1	67	14	8	4.1	82.7	27.8	868
4.4	6.2	66	15	8	4.2	83.6	28.2	789
2.7	6.3	59	22	7	4.4	83.1	28.2	840
2.5	6.1	57	23	8	4.2	83.4	28.0	889
2.5	6.5	60	24	9	4.3	83.5	27.6	878

soil's Ca saturation was <65%, and Mg saturations ranged from 18 to 28% (c.f. the "balanced" value of 10%). Schonbeck found, however, that even though the addition of Ca amendments reduced the Mg saturation to 11 to 21%, there was no detectable effect on crop Brix (soluble solids, an index of produce quality). Similarly, Kelling et al. (1996) concluded that the Ca/Mg ratio in Wisconsin soils had no significant effect on alfalfa quality (crude protein, acid detergent fiber, and neutral detergent fiber) or yield.

Under certain conditions, Mg deficiency (hypomagnesaemia) has been observed in livestock, even when Mg concentrations were sufficient for plant growth. This is particularly problematic in cool, wet (temperate) conditions when the dry mass per unit of fresh grass is lower, and hence the Mg consumed by the livestock may be reduced (Grunes et al., 1970). Similarly, grasses often have lower shoot Mg concentrations than legumes (Grunes et al., 1970). Thus, where grass crops are to be used for forage and soil Mg concentrations are low, additional Mg may be required. Additionally, the Mg concentration of the "ideal soil" may not be sufficient to meet livestock requirements (McLean and Carbonell, 1972).

Soil Physical Properties

The balanced soil paradigm also postulates an effect of cation ratios on plant growth through changes in soil structure, in particular, surface-crusting, compaction, and decreased hydraulic conductivity (i.e., increased runoff). The high exchangeable Ca content (65%) of a "balanced soil" is undoubtedly beneficial in maintaining and improving soil structure and aggregate stability (see Amézketa [1999] for a review). The concern arises, however, that if the soil Ca content is lower (and the Mg higher) than that recommended by the BCSR, then soil structure may decline. This concern is based on the observation that soil aggregates 100% saturated with Ca are less likely to disperse than those saturated with Mg (Rengasamy, 1983; Zhang and Norton, 2002). While a "balanced soil" is likely to have good structure, however, this structure can be maintained across a range of Ca/Mg ratios. For example, Rengasamy et al. (1986) demonstrated that the structure of a red-brown earth (Rhodoxeralf) (as measured by hydraulic conductivity) was maintained across a variety of Ca/Mg ratios (Fig. 7). Indeed, when soils contained low Na concentrations (i.e., at an sodium adsorption ratio (SAR) of 3), hydraulic conductivity was no different when there was twice as much Mg as Ca (Ca:Mg 0.5:1) to that when there was 2.5 times more Ca than Mg (Ca:Mg 2.5:1) (Fig. 7). Even when the Na concentration was high (Na adsorption ratio of 20), there was no difference between hydraulic conductivity achieved at a Ca/Mg of 2.5:1 and that achieved at a 1:1 ratio (Fig. 7).

These laboratory observations of Rengasamy et al. (1986) have been confirmed in the field. In the on-farm trials of Schonbeck (2000), the poor hydraulic conductivity, crusting, and hardpans observed on these soils had often been attributed by the farmers to the cationic "imbalance" of the soil. Reduction in the Mg saturation from 18 to 28% to 11 to 21%, however, had no effect on bulk density (compaction), moisture content, infiltration rate, or soil strength. In fact, the two soils that were the most "unbalanced" (Mg 28%, Ca 59%) actually had the best physical properties.

Soil Biological Activity

The provision of "balanced" cation ratios has been claimed to improve the soil's biological activity, and decrease weed growth and insect attack. Comparatively little information is available, however, comparing the biological fertility in "balanced soils" to that in soils containing other cationic ratios. Nevertheless, in the trials of Schonbeck (2000), a reduction in Mg saturation (from 18–28 to 11–21%) had no detectable effect on soil organic matter, biological activity, abundance of weeds, or incidence of disease or insect pest damage compared with the control treatment. Similarly, Kelling et al. (1996) concluded that variation in the Ca/Mg ratio had no significant effect on the earthworm population or on the growth of weeds (grass or broadleaf).

CONCLUSIONS

While the origin of the "ideal" or "balanced" soil concept can be traced back to the late 1800s, it was primarily through work conducted in the 1940s by Bear and coworkers in New Jersey that led to the concept of an "ideal" soil being one with 65% Ca, 10% Mg, and 5% K. Based on this work and on his own work in the 1930s and 1940s, Albrecht promoted the use of the "balanced soil," suggesting that optimal growth will only occur in soils containing the "ideal" composition. It would appear, however, that the soil's chemical, physical, and biological fertility can be maintained across a range of cationic ratios. Indeed, McLean, who worked with Albrecht in Missouri during the 1940s, stated that, on the whole, "there is no 'ideal' basic cation saturation ratio or range" (Eckert and McLean, 1981), and that "emphasis should be placed on providing sufficient, but not excessive levels of each basic cation rather than attempting to attain a favorable basic cation saturation ratio which evidently does not exist" (McLean et al., 1983). The data do not support the claims of the BCSR, and continued promotion of the BCSR will result in the inefficient use of resources in agriculture and horticulture.

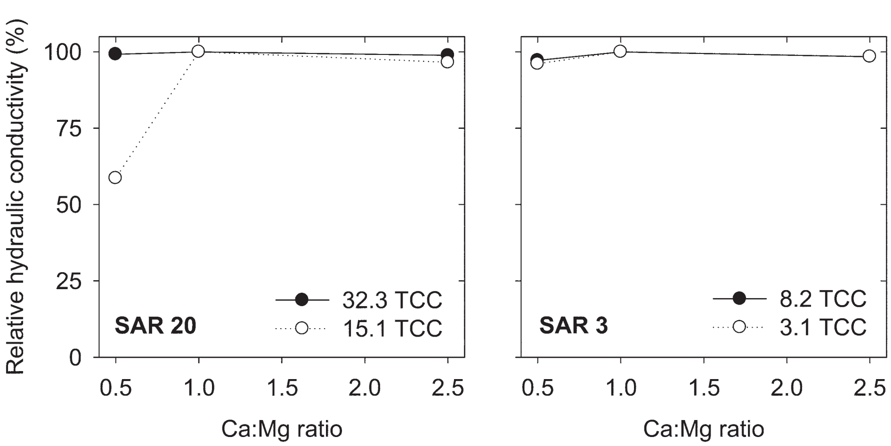

Fig. 7. Effects of the Ca/Mg ratio, sodium adsorption ratio (SAR), and salinity (presented as the total cation concentration [TCC, $mmol_c$/L]) on the relative hydraulic conductivity of a surface soil of a sodic red-brown earth (Rhodoxeralf). The relative hydraulic conductivity has been calculated separately for each TCC series. Data taken from Rengasamy et al. (1986).

ACKNOWLEDGMENTS

We acknowledge Dr. Mal Hunter, Dr. Gunnar Kirchhof, Dr. Peter Dart, Professor Richard Burns, and Dr. Pax Blamey for their generous assistance in preparing this work. Data in Table 1 is taken from Steves et al. (2005), in Journal of cotton Science 9:65-71, and is reproduced with permission of Dr. Gene Stevens.Data in Fig. 7 is taken from Table 3 in Rengasamy et al. (1986), in: Australian Journal of Soil Research 23(2):229-237., and is reproduced with permission of CSIRO Publishing, Melbourne, Australia.

REFERENCES

Aitken, R.L., and B.J. Scott. 1999. Magnesium. p. 255–262, *In* K.I. Peverill et al. (ed.) Soil analysis: An interpretation manual. CSIRO Publ., Melbourne, Australia.

Albrecht, W.A. 1937. Physiology of root nodule bacteria in relation to fertility levels of the soil. Soil Sci. Soc. Am. Proc. 2:315–327.

Albrecht, W.A. 1939. Some soil factors in nitrogen fixation by legumes. Trans. 3rd Commiss. of the Int. Soc. of Soil Sci., New Brunswick, NJ.

Albrecht, W.A. 1975. The Albrecht papers. Vol. 1: Foundation concepts. Acres USA, Kansas City.

Albrecht, W.A., and T.M. McCalla. 1938. The colloidal fraction of the soil as a cultural medium. Am. J. Bot. 25:403–407.

Albrecht, W.A., and G.E. Smith. 1941. Biological assays of soil fertility. Soil Sci. Soc. Am. Proc. 6:252–258.

Alva, A.K., D.G. Edwards, C.J. Asher, and S. Suthipradit. 1987. Effects of acid soil infertility factors on growth and nodulation of soybean. Agron. J. 79:302–306.

Amézketa, E. 1999. Soil aggregate stability: A review. J. Sustain. Agric. 14:83–151.

Bear, F.E., A.L. Prince, and J.L. Malcolm. 1945. Potassium needs of New Jersey soils. Bull. 721. New Jersey Agric. Exp. Stn., New Brunswick.

Bear, F.E., A.L. Prince, S.J. Toth, and E.R. Purvis. 1951. Magnesium in plants and soil. Bull. 760. New Jersey Agric. Exp. Stn., New Brunswick.

Bear, F.E., and S.J. Toth. 1948. Influence of calcium on availability of other cations. Soil Sci. 65:69–74.

Bruce, R.C. 1999. Calcium. p. 247–254. *In* K.I. Peverill et al (ed.) Soil analysis: An interpretation manual. CSIRO Publ., Melbourne, Australia.

Bruce, R.C., L.A. Warrell, D.G. Edwards, and L.C. Bell. 1988. Effects of aluminium and calcium in the soil solution of acid soils on root elongation of *Glycine max* cv. Forrest. Aust. J. Agric. Res. 39:319–338.

Budavari, S. 1989. The Merck index: An encyclopedia of chemicals, drugs, and biologicals. 11th ed. Merck & Co., Rahway, NJ.

Eckert, D.J. 1987. Soil test interpretations: Basic cation saturation ratios and sufficiency levels. p. 53–64. *In* J.R. Brown (ed.) Soil testing: Sampling, correlation, calibration, and interpretation. SSSA Spec. Publ. 21. SSSA, Madison, WI.

Eckert, D.J., and J. McLean. 1981. Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops: I. Growth chamber studies. Agron. J. 73:795–799.

Foy, C.D. 1984. Physiological effects of hydrogen, aluminium, and manganese toxicities in acid soil. p. 57–97. *In* F. Adams (ed.) Soil acidity and liming. Agron. Monogr. 12. 2nd ed. ASA, CSSA, and SSSA, Madison, WI.

Giddens, J., and S.J. Toth. 1951. Growth and nutrient uptake of ladino clover on red and yellow grey-brown podzolic soils containing varying ratios of cations. Agron. J. 43:209–214.

Gourley, C.J.P. 1999. Potassium. p. 229–245. *In* K.I. Peverill et al (ed.) Soil analysis: An interpretation manual. CSIRO Publ., Melbourne, Australia.

Graham, E.R. 1959. An explanation of theory and methods of soil testing. Bull. 734. Missouri Agric. Exp. Stn., Columbia.

Grunes, D.L., P.R. Stout, and J.R. Brownell. 1970. Grass tetany of ruminants. Adv. Agron. 22:331–374.

Haby, V.A., M.P. Russelle, and E.O. Skogley. 1990. Testing soils for potassium, calcium, and magnesium. p. 181–227. *In* R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, Wisconsin.

Harston, C.B., and W.A. Albrecht. 1942. Plant nutrition and the hydrogen ion. IV: Soil acidity for improved nutrient delivery and nitrogen fixation. Soil Sci. Soc. Am. Proc. 7:247–257.

Hissink, D.J. 1925. Base exchange in soils. Trans. Faraday Soc. 20:551–556.

Hunter, A.S. 1949. Yield and composition of alfalfa as influenced by variations in the calcium–magnesium ratio. Soil Sci. 67:53–62.

Hunter, A.S., S.J. Toth, and F.E. Bear. 1943. Calcium–potassium ratios for alfalfa. Soil Sci. 55:61–72.

Hutchings, T.B. 1936. Relation of phosphorus to growth, nodulation and composition of soybeans. Bull. 243. Missouri Agric. Exp. Stn., Columbia.

Kamprath, E.J. 1971. Potential detrimental effects from liming highly weathered soils to neutrality. Proc. Soil Crop Sci. Soc. Fla. 31:200–203.

Kelling, K.A., E.E. Schulte, and J.B. Peters. 1996. One hundred years of Ca: Mg ratio research. New Horiz. in Soil Ser. 8. Dep. of Soil Sci., Univ. of Wisconsin, Madison.

Key, J.L., L.T. Kurtz, and B.B. Tucker. 1962. Influence of ratio of exchangeable calcium–magnesium on yield and composition of soybeans and corn. Soil Sci. 93:265–270.

Liebhardt, W.C. 1981. The basic cation saturation ratio concept and lime and potassium recommendations on Delaware's Coastal Plain soils. Soil Sci. Soc. Am. J. 45:544–549.

Lipman, C.B. 1916. A critique of the hypothesis of the lime/magnesia ratio. Plant World 19:83–105, 119–133.

Llugany, M., C. Poschenrieder, and J. Barcelo. 2000. Assessment of barium toxicity in bush beans. Arch. Environ. Contam. Toxicol. 39:440–444.

Loew, O. 1892. Uber die physiolgischen funkton der kalzium- und magnesia-salze in planzen organisms. Flora 75:368–394.

Loew, O., and D.W. May. 1901. The relation of lime and magnesia to plant growth. USDA Bur. of Plant Industries Bull. 1. USDA, Washington, DC.

McLean, E.O. 1977. Contrasting concepts in soil test interpretation: Sufficiency levels of available nutrients versus basic cation saturation ratios. p. 39–54. *In* T.R. Peck et al. (ed.) Soil testing: Correlating and interpreting the analytical results. ASA Spec. Publ. 29. ASA, CSSA, and SSSA, Madison, WI.

McLean, E.O., and M.D. Carbonell. 1972. Calcium, magnesium, and potassium saturation ratios in two soils and their effects upon yield and nutrient contents of German millet and alfalfa. Soil Sci. Soc. Am. Proc. 36:927–930.

McLean, E.O., R.C. Hartwig, D.J. Eckert, and G.B. Triplett. 1983. Basic cation saturation ratios as a basis for fertilizing and liming agronomic crops: II. Field studies. Agron. J. 75:635–639.

McLean, E.O., G.E. Smith, and W.A. Albrecht. 1943. Biological assays of some soil types under treatments. Soil Sci. Soc. Am. Proc. 8:282–286.

Moser, F. 1933. The calcium–magnesium ratio in soils and its relation to crop growth. J. Am. Soc. Agron. 25:365–377.

Ologunde, O.O., and R.C. Sorensen. 1982. Influence of concentrations of K and Mg in nutrient solutions on sorghum. Agron. J. 74:41–46.

Olson, R.A., K.D. Frank, P.H. Grabouski, and G.W. Rehm. 1982. Economic and agronomic impacts of varied philosophies of soil testing. Agron. J. 74:492–499.

Prince, A.L., M. Zimmerman, and F.E. Bear. 1947. The magnesium-supplying powers of 20 New Jersey soils. Soil Sci. 63:69–78.

Rengasamy, P. 1983. Clay dispersion in relation to changes in the electrolyte composition of dialyzed red-brown earths. J. Soil Sci. 34:723–732.

Rengasamy, P., R.S.B. Greene, and G.W. Ford. 1986. Influence of magnesium on aggregate stability in sodic red-brown earths. Aust. J. Soil Res. 24:229–237.

Schinas, S., and D.L. Rowell. 1977. Lime-induced chlorosis. J. Soil Sci. 28:351–368.

Schonbeck, M. 2000. Balancing soil nutrients in organic vegetable production systems: Testing Albrecht's base saturation theory in southeastern soils. Organic Farming Res. Found. Inf. Bull. 10:17.

Smith, G.E., and W.A. Albrecht. 1942. Feed efficiency in terms of biological assays of soil treatments. Soil Sci. Soc. Am. Proc. 7:322–330.

Stevens, G., T. Gladbach, P. Motavalli, and D. Dunn. 2005. Soil calcium:magnesium ratios and lime recommendations for cotton. J. Cotton Sci. 9:65–71.

Watanabe, T., and K. Okada. 2005. Interactive effects of Al, Ca and other cations on root elongation of rice cultivars under low pH. Ann. Bot. 95:379–385.

Western Australian No-Tillage Farmers Association. 2005. WANTFA Meckering R&D Site Trial Results 2004. WANTFA, Perth, Western Australia.

Zhang, X.C., and L.D. Norton. 2002. Effect of exchangeable Mg on saturated hydraulic conductivity, disaggregation and clay dispersion of disturbed soils. J. Hydrol. 260:194–205.