

Historical Perspective of Soil Balancing Theory and Identifying Knowledge Gaps: A Review

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Abstract

The common philosophies that contextualize soil test results and fertilizer recommendations are sufficiency level of available nutrients (SLAN), buildup and maintenance, and basic cation saturation ratio (BCSR). The BCSR approach postulates maintaining an ideal ratio of basic cation (Ca^{2+} , Mg^{2+} , and K^+) saturations on the soil exchange sites to maximize crop yields. The practice of adding amendments to alter the ratios of basic cation saturations in soils is called "soil balancing." Bear, Graham, and Albrecht promoted this concept, with each suggesting a desired saturation ratio of Ca:Mg:K for optimum crop yields. Several researchers have tried to validate this theory with both greenhouse and field experiments but could not conclude that an ideal cation saturation ratio existed and found that crop yields were similar across a wide range of ratios. While the scientific community disregards this theory, some farmers, crop consultants, and commercial soil-testing laboratories still use BCSR to guide their fertilizer recommendations. It is believed that soil balancing effectively controls weeds, insects, and pests and improves overall soil health for better plant growth, ultimately producing better crop yields. Some even argue that soil balancing improves nutritional quality of the harvested crop. However, contemporary research to objectively demonstrate such perceived benefits of practicing soil balancing is missing. This review presents a holistic overview of soil balancing, presents a literature review on BCSR, and identifies knowledge gaps, which need to be addressed to better understand the merits and limitations of soil balancing.

Soil fertility testing is a valuable tool to make informed nutrient management decisions. Three main philosophies exist to interpret soil test reports and provide appropriate fertilizer recommendations. Those include (i) sufficiency level of available nutrients (SLAN), (ii) buildup and maintenance, and (iii) basic cation saturation ratio (BCSR) concepts (Black, 1993). The SLAN approach works on the principle that there are certain critical levels of individual nutrients. If a soil tests above the critical level, the crop will not likely respond to fertilization but if the soil tests below the critical level, the crop will respond to fertilization (Eckert, 1987). The buildup-and-maintenance approach calls for a gradual buildup of soil nutrient levels above the critical levels over time, and then to maintain these levels by replacing the amounts of each nutrient

Reviews



Core Ideas

- A soil with an ideal basic cation saturation ratio (BCSR) is said to maximize crop yields.
- Previous studies concluded higher crop yields are possible over a wide range of ratios.
- Scientific community generally disregards BCSR theory.
- Soil balancing effects on weeds, soils, and crop quality are critical knowledge gaps.

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Abbreviations: BCSR, basic cation saturation ratio;
CEC, cation exchange capacity; SLAN, sufficiency level
of available nutrients.

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removed by the crop at harvest (Olson et al., 1987; Black, 1993; Voss, 1998). The focus here is to always maintain the soil fertility status at a high level with constant fertilizer applications, so that yields are sustained. The third approach is the BCSR, which recommends an optimum or ideal calcium (Ca), magnesium (Mg), and potassium (K) saturation ratio on the soil exchange complex to achieve maximum crop yields (McLean, 1977; Voss, 1998). With BCSR, fertilizer recommendations are made to adjust the cation saturation ratios to an optimum or ideal level, irrespective of actual soil nutrient levels. A soil with such an optimal saturation ratio of base cations is considered to be a balanced soil and the practice of adding fertilizer/amendments to achieve a desired ratio is called “soil balancing.” Generally, the SLAN approach recommends fertilizing based on plant needs, the buildup-and-maintenance approach focuses on fertilizing the soil, and BCSR targets on countering the mineral imbalances in soil (Black, 1993; Eckert, 1987). In contrast to sufficiency level and buildup-and-maintenance philosophies, BCSR focuses only on Ca, Mg, and K and does not directly relate to the availability of nitrogen (N), phosphorus (P), sulfur (S), or micronutrients (Eckert, 1987).

There is an apparent discrepancy in using different philosophies for soil fertilizer recommendation programs. However, over the past three decades, ongoing research by soil fertility scientists on soil testing, interpretation, and calibration has resulted in the adoption of SLAN and buildup-and-maintenance philosophies or a hybrid of these two, as a standard fertilizer recommendation practice by land-grant universities. On the other hand, some commercial soil-testing laboratories employ BCSR and buildup-and-maintenance approaches in their lime and fertilizer recommendation programs (Voss, 1998). To date, there is little published research that substantiates the BCSR theory and the concept of a balanced soil for maximizing yields, and only a few studies have tested its efficacy. Still, some agronomists, consultants, commercial soil-testing labs, and farmers strongly subscribe to this practice and continue to use it to guide their soil management decisions and nutrient recommendations. This review (i) presents a brief history of the BCSR theory, (ii) provides an overview of the research that has been conducted on BCSR and crop production, and (iii) identifies knowledge gaps that need attention.

What is Basic Cation Saturation?

Soil nutrients can exist in many forms, but the nutrients that plants take up are mostly positively (cations) or negatively (anions) charged ions. Cations and anions are available in soil solution or on the soil exchange sites. Those that are in soil solution are readily available to plants. Cation exchange sites are negatively charged surfaces of clay and organic matter that attract and hold cations in the soil. Soil tests measure the sum of these exchange sites and report them as cation exchange capacity (CEC). The CEC is a defining feature of soils, and the greater the CEC of a soil, the more cations it can hold (Hazelton and Murphy, 2007). Cations are generally classified as “basic” and “acidic” based on their influence

on soil pH through various soil reactions. Basic cations (also called as nonacidic cations) include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+). Acidic cations consist of hydrogen (H^+) and aluminum (Al^{3+}). Figure 1 shows different basic and acidic cations on soil exchange sites. Base saturation indicates the proportion of these basic cations that occupy the soil exchange sites (CEC). In other words, if a soil has a 50% base saturation of Ca, then Ca occupies 50% of the exchange sites. Figure 2 gives a pictorial representation of the base saturations of Ca^{2+} at approximately 60%, Mg^{2+} at approximately 15%, and K^+ at approximately 5%, making up to approximately 80% of the total CEC of the soil. Remaining sites (approximately 20% of CEC) could be occupied by other basic cations, such as Na^+ , or acidic cations such as H^+ and Al^{3+} . However, BCSR is primarily concerned with the percent saturation of only Ca^{2+} , Mg^{2+} , and K^+ ions on the exchange sites.

Development of Basic Cation Saturation Ratio Theory

The concept of BCSRs and their influence on plant growth was conceptualized in the late 1800s when Leow first suggested the presence of an optimal Ca:Mg ratio in soil. However, it was the work of Bear and his coworkers in New Jersey and William Albrecht at the University of Missouri that promoted BCSR, which became a major subject of interest during that time. In the early 1940s, Bear and his coworkers from New Jersey were trying to reduce luxury consumption of K by alfalfa (*Medicago sativa* L.) and proposed the concept of an “ideal soil.” According to these authors, an “ideal soil” should consist of 65% Ca, 10% Mg, 5% K, and 20% H on the soil exchange sites (Bear et al., 1945). This translates into a BCSR of 13:2:1. However, Graham (1959) modified these numbers and proposed that percent saturations could range from 60 to 85% for Ca, 6 to 12% for Mg, and 2 to 5% for K, and plant yields would not differ significantly when saturations were maintained anywhere between these ranges. After reviewing his own work and that of Bear and Graham, William Albrecht concluded that a balanced soil should have 60 to 75% Ca, 10 to 20% Mg, 2 to 5% K, 10% H, and 5% of other cations to maximize crop yields (Albrecht, 1975). Later, Baker and Amacher (1981) also proposed different ranges for an ideal base saturation. Nevertheless, the work of Bear and Albrecht really laid the foundation for the BCSR concept and thereafter scientists have conducted studies to evaluate this theory on yields of major agronomic crops.

Research on Basic Cation Saturation Ratio and Crop Production

The existence of BCSR theory dates back almost 100 years but it was not until late 1930s and early 1940s that it gained momentum and attention of researchers. This article mainly focuses on research that was published after 1930s. Table 1 presents a list of major published studies and provides the details and key conclusions of the studies that looked into various basic cation ratios and their effect on crop yields. A more thorough review of published literature on BCSR can

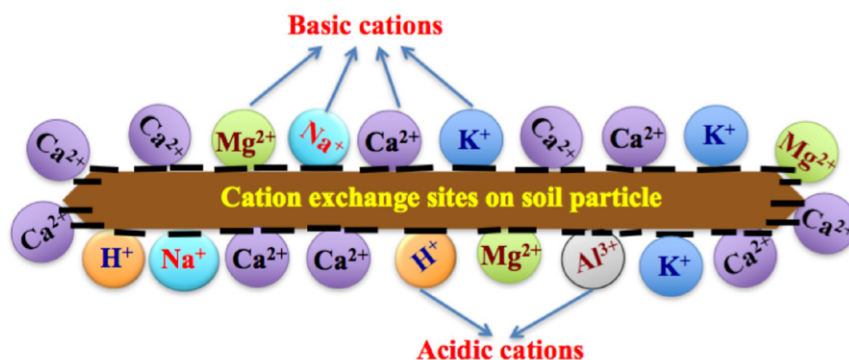


Fig. 1. Saturation of soil exchange complex with basic and acidic cations.

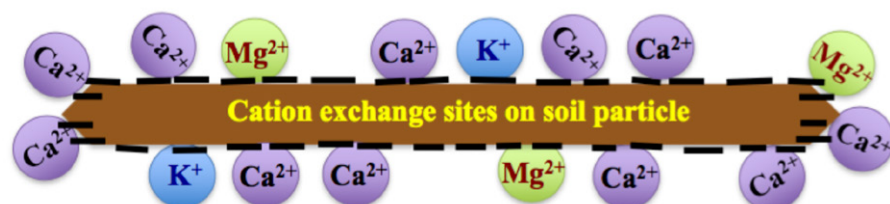


Fig. 2. Proportion of base cations on soil exchange sites.

Table 1. List of major studies that evaluated basic cation saturation ratio (BCSR) on crop yields.†

| Author and year | Greenhouse–field experiments | Experiment objectives | Measured variables | Major conclusions |
|----------------------------|--|---|--|---|
| Moser, 1933 | Greenhouse cylinder experiments at Cornell Agricultural Experiment Station | Test the effects of varying Ca:Mg ratios on crop growth | Yields of barley, red clover, corn, and timothy grass | No significant correlation between cation ratios and crop yields. Yields increased only due to the availability of more active Ca in the soil |
| Hunter et al., 1943 | Greenhouse experiments | Effect of Ca:K ratios on alfalfa yield in soil–sand mixtures | Harvest yield of alfalfa, root biomass, tissue Ca and K levels | Alfalfa can tolerate wide range of Ca:K ratios without any significant yield differences, as long as adequate levels of Ca and K were maintained |
| Hunter, 1949 | Greenhouse pot experiments | Effect of Ca:Mg ratios on yield and mineral composition of alfalfa | Yield, weight of roots, tissue percentages of P, Ca, Mg, K, and lignin content | No effect of varying ratios of Ca:Mg were observed on both alfalfa yield and root weight |
| Giddens and Toth, 1951 | Greenhouse pot experiments | Effect of Ca:Mg ratios on yield and plant uptake of nutrients by ladino clover (<i>Trifolium repens</i> L.) | Yield and mineral composition of tops and roots | No effect of cation ratios on yields. Increase in Ca, Mg, and K in soil caused an increased uptake of these nutrients by plants |
| Key et al., 1962 | Greenhouse experiments in Illinois | Evaluate the growth of corn and soybean under varying Ca:Mg ratios in two different media (soil and resin-sand) with different CECs | Yield of soybean and corn | Yields of corn and soybean were not significantly affected by varying Ca:Mg ratio, when grown in soil media. Yields of soybeans and corn grown in resin media were reduced when ratios fell less than 1:1 |
| McLean and Carbonell, 1972 | Greenhouse pot experiments at The Ohio Agricultural Research and Development Center, Wooster | Test the effects of varying Ca-Mg saturations in soils of two different CECs | Yield and Ca, Mg, and K contents of alfalfa and German millet [<i>Setaria italica</i> (L.) P. Beauv.] crops | Yields of both crops were not significantly affected by varying saturations of Ca and Mg. Concluded that 6–10% of Mg is ideal for most crops but 12–15% is ideal when grasses are grown for feed to reduce Mg deficiency in animals |
| Simson et al., 1979 | Field trials in Wisconsin | Study the effects of varying Ca:Mg ratios on yield of corn and alfalfa | Yield and tissue concentrations in corn and alfalfa | No significant yield responses were observed in relation to Ca and Mg applications in both corn and alfalfa |

Cont'd.

Table 1. Continued.

| Author and year | Greenhouse–field experiments | Experiment objectives | Measured variables | Major conclusions |
|-------------------------|---|--|---|---|
| Eckert and McLean, 1981 | Greenhouse experiments in northern Ohio | Evaluate crop growth with variable cation ratios | Yield of millet and alfalfa | No maximum yield was observed at any particular ratio or base saturation percentage. General yield increases were observed at higher pH values. No best ratio existed for maximizing yields for both crops |
| Liebardt, 1981 | Field experiment at the Univ. of Delaware Georgetown experiment station | Effects of various Ca, Mg and K saturations on corn and soybean yields | Grain yields and tissue levels of corn and soybean | K saturation of 2–2.5% is enough in Delaware soils and no probable grain yield increase above 2.5%. Wide Ca:Mg ratios meet nutrient requirements of corn and soybeans |
| McLean et al., 1983 | Field experiment in Wooster, OH | (i) To identify an ideal BCSR where yields are maximized (ii) To examine the effects of adding Ca, Mg, and K based on SLAN, on yield and tissue composition (iii) To test the merits of BCSR and SLAN concept for lime and K recommendations | Crop yield and tissue concentrations for six crops (corn, corn, soybeans, wheat, alfalfa, and alfalfa) over 6 years | Associations between cation ratios and crop yield were low, indicating no particular ratio of either Ca:Mg or Mg:K produced higher yields. SLAN concept is superior to BCSR and application of cations based on sufficiency levels is recommended |
| Fox and Piekielek, 1984 | Field experiments on Research farms at Pennsylvania State Univ. | Effects of Ca:Mg ratios (1.8–36.9) on corn grain yields and Mg levels needed to ensure 0.2% Mg in silage corn | Corn yields, tissue Mg concentrations | No effect of Ca:Mg ratios on corn grain yields. 10% soil Mg saturation needed to have 0.2% tissue level in silage corn |
| Rehm and Sorensen, 1985 | Field experiments in north-central Nebraska | Effects of Mg:K ratios on corn yields and uptake of Mg and K | Corn yields, tissue K and Mg concentrations | Mg:K ratios did not affect yields. K uptake was not inhibited at high Mg levels, but Mg uptake was reduced at higher K levels |
| Reid, 1996 | Field experiments at Cornell Univ. | Effect of different rates of liming and resulting Ca:Mg ratios on alfalfa and birdsfoot trefoil (<i>Lotus corniculatus</i> L.) hay yields | Yields of alfalfa and birdsfoot trefoil | Various Ca:Mg ratios did not have any significant yield differences. General increase in yields was due to a rise in pH by liming with maximum yield at pH 6.5 |
| Stevens et al., 2005 | Field experiments at Univ. of Missouri Lee farm | Effects of Ca:Mg ratios on cotton (<i>Gossypium hirsutum</i> L.) lint yield and fiber quality | Soil characteristics, cotton K uptake, lint yield, and fiber quality | No significant effect of varying Ca:Mg ratios was observed on lint yield, fiber quality, and K uptake. BCSR theory did not show any advantage in managing cotton crop in well-drained Delta soils |
| Favaretto et al., 2008 | Greenhouse experiment at Purdue Agricultural Center | Effects of gypsum and various Ca:Mg ratios on nutrient availability in soil and corn root and shoot growth | Soil nutrient status, root and shoot dry matter | Root and shoot dry matter differences were nonsignificant between various Ca:Mg ratios |

† CEC, cation exchange capacity; SLAN, sufficiency level of available nutrients.

be found in Kopittke and Menzies (2007). The common outcome of every study that has been conducted for crop yield response to varying cation ratios was refuting the existence of an ideal ratio or a balanced soil. Findings from these published studies failed to support the claim of the BCSR theory that a particular saturation ratio results in higher yields. For instance, Eckert and McLean at The Ohio State University conducted several greenhouse and field trials over 5 years, testing the effect of varying cation ratios on yields of corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], wheat (*Triticum aestivum* L.), and alfalfa. They concluded that there is no ideal ratio of cations that produced higher yields. Similarly, Jay W. Johnson at Ohio State conducted field trials from 1976 to

1980 and also concluded that there is no optimum Ca:Mg:K ratio that produced higher yields in either corn or soybean (unpublished data, 1980). Results from these studies suggest that plants tolerate a wide range of cation ratios as long as they do not experience any deficiencies.

The BCSR approach can result in expensive overapplication of soil amendments to achieve a desired cation saturation ratio, even when there are adequate amounts of these nutrients in the soil to satisfy crop demands (Eckert, 1987; Black, 1993). Previous studies have compared the three fertilizer recommendation philosophies in their adequacy to satisfy both agronomic and economic interests of producers.

A study conducted by Olson et al. (1982) in Nebraska demonstrates such agronomic and economic viability of different recommendation philosophies provided by four different soil-testing laboratories and comparing those to the university recommendation of sufficiency level approach. Corn grain yields, average nutrients applied, and average fertilizer costs were evaluated over an 8-year period. The authors of this study reported that sufficiency level approach was far superior and produced the most economic yields compared with the other two philosophies (Olson et al., 1982). Similarly, McLean et al. (1983) and Murdock (1992) also concluded that sufficiency level approach was the most economical and BCSR approach as the most expensive option with no yield advantage from excessive fertilizer applications. Therefore, it was advised that maintaining sufficient, but not excessive, levels of these base cations is more important to perform their specific functions in plants rather than striving for an optimum cation ratio in a soil (Black, 1993; Gaspar and Laboski, 2016; McLean et al., 1983; Rehm, 1994).

Basic Cation Saturation Ratio and Knowledge Gaps

Scientific literature regarding the BCSR is scant and focused mainly on crop yields. While most soil scientists disregard soil balancing theory, some farmers and other stakeholders (private soil-testing labs, crop consultants) follow the soil balancing approach. For example, in a survey of organic farmers in Ohio and Indiana, about 60% follow soil balancing practices (Zwickle et al., 2014). Survey work has demonstrated organic farmer beliefs that soil balancing can help control weeds, improve crop growth, and improve nutritional quality of crops, relative to those grown on soils using the sufficiency level approach. Farmers from across other regions of the country have also expressed similar beliefs about soil balancing. However, there is a lack of scientific knowledge supporting these claims and similar knowledge gaps exist regarding soil balancing in relation to pest and disease management in crops.

Despite the lack of documented effects of BCSR on crop productivity, research has demonstrated the essential role that basic cations such as Ca^{2+} , Mg^{2+} , and Na^+ play in altering soil structure and aggregate stability. Soil structure and aggregate stability are prime soil physical quality indicators, and maintaining good soil structure promotes better plant growth by facilitating better seed establishment, root growth and development, aeration, and water infiltration (Bronick and Lal, 2005). The role of cations in influencing soil structure and aggregation is well understood. Cations help form bridges between organic and clay surfaces at the molecular level and facilitate soil aggregation. Generally, multivalent cations (cations with more than one charge such as Ca^{2+} , Mg^{2+} , Al^{3+}) are more involved in forming these bridges than monovalent cations (cations such as Na^+ , K^+) (Amézketa, 1999). Moreover, multivalent cations better create attractive forces between two soil particles and help keep them together, whereas monovalent cations create repulsive forces and separate individual soil particles thus causing soil

aggregate disruption (Hillel, 2013). In addition to the ionic valency, hydrated radius is an important attribute of an ion that determines its ability to either flocculate or deflocculate soil particles (Rao and Mathew, 1995).

Calcium and Magnesium Role in Soil Aggregation

Predominant cations that influence soil aggregation and structure are Na^+ , Ca^{2+} , and Mg^{2+} . Beneficial effects of cations on soil structure and aggregate stability are given in the order of $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$ (Amézketa, 1999). Sodium is a major soil dispersant and adversely affects soil structure by disrupting soil aggregates. In contrast, Ca and Mg facilitate soil binding and promote soil aggregation. Gypsum is a common soil amendment used on dispersed soils to improve their soil structure by supplying Ca to replace Na. Comparing Ca and Mg, Ca generally tends to be more efficient than Mg (Curtin et al., 1994) in binding soil particles and is often a preferred cation at the exchange sites due to its smaller hydrated radius than Mg (Rao and Mathew, 1995). Calcium also facilitates the formation of stronger and more stable aggregates due to its higher flocculating power than Mg (Rengasamy and Sumner, 1998). Magnesium, by virtue of its ionic properties (larger hydration radius and less flocculating power than Ca), could deteriorate soil structural quality by dispersing clay particles (Fig. 3) and promote aggregate breakdown, when present as the dominant cation or at extremely high concentrations in the soil (Emerson and Chi, 1977). Zhang and Norton (2002) demonstrated this effect with excess Mg promoting disaggregation and causing reduced pore space due to clay dispersion. In a related study, Dontsova and Norton (2002) studied the effect of different Ca:Mg ratios on surface sealing, water infiltration, and runoff in Midwestern soils under simulated rainfall conditions. They observed that higher Mg saturations increased surface sealing with aggregate destruction and total infiltration was reduced to half of that on high Ca-saturated soils. However, the key here is that these studies tested the effect of Mg at saturations exceeding 75%, which is unrealistic of field conditions. Magnesium saturations on soil cation exchange sites would rarely exceed 30%, especially in Midwestern soils.

Basic cation saturation ratio theory generally postulates maintaining higher Ca saturation than Mg on the exchange sites (Albrecht, 1975). So, it is very likely that a “balanced soil” will have good soil physical quality. However, there is no scientific evidence to support the belief that a “balanced soil” has better structure and aggregate stability than an “unbalanced soil” in terms of soil physical quality. Mere assumption that a soil might have structural and aggregation problems due to its unbalanced cation ratios is not justified as unbalanced soils nearly always have higher Ca saturation than Mg, and previous work has shown that soil structure can be maintained over a wide range of Ca:Mg ratios (Rengasamy et al., 1986).

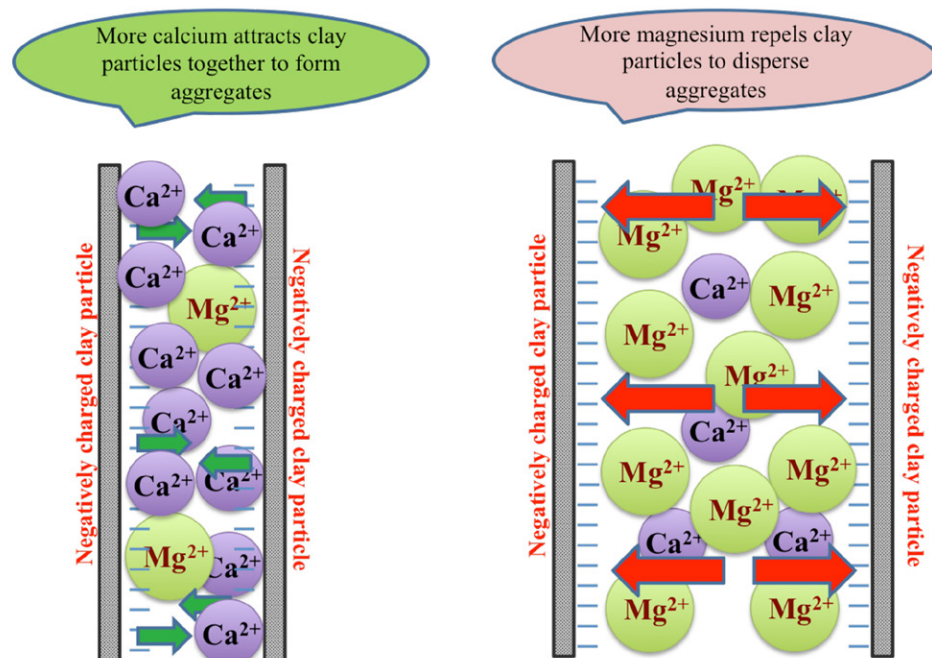


Fig. 3. Possible effects of Ca^{2+} and Mg^{2+} cations on soil aggregation.

Cation Nutrient Interactions

Nutrient interaction is a process where the presence of one nutrient in excess affects the plant uptake of other nutrients and may lead to a deficiency of those nutrients in the plant. Nutrient ion interactions are complex and could have either synergistic or antagonistic effects based on their combined effect on plant growth and yield (Fageria, 2001). Common cation interactions include those among K^+ , Na^+ , Ca^{2+} , and Mg^{2+} . Previous studies have revealed that excess K in soil can limit the uptake of both Ca and Mg from soil and vice versa. For example, Jakobsen (1993) showed that excess K in soil reduced Ca and Mg uptake by corn and resulted in their deficiencies in plants. Similar antagonistic effects between K^+ , Ca^{2+} , and Mg^{2+} ions were reported by several other researchers (Dibb and Thompson, 1985; Grunes et al., 1992; Keisling et al., 1979; Rehm and Sorensen, 1985; Smith, 1975). While most of these nutrient interactions take place between ions in the soil solution, the role of exchangeable cations cannot be ignored as these buffer the changes in solution ion concentrations. Amendment applications made to achieve an ideal Ca, Mg, and K saturation ratio and that exceed plant requirements could alter the balance of Ca^{2+} , Mg^{2+} , and K^+ ions in soil solution and thereby influence nutrient interactions. A clear understanding of the relationship between soil balancing and nutrient interactions is lacking and merits investigation.

Conclusion

Basic cation saturation ratio is a controversial theory with no substantial scientific evidence to support its claim of maintaining an ideal ratio of cations to maximize crop yields. There is a wide disconnect in the perception of using this theory for fertilizer recommendations. While scientific

researchers disregard BCSR, some growers and agronomists use this framework for guiding soil and crop management decisions. Previous research has always focused on testing this theory on crop yields. But the BCSR proponents attest that soil balancing is a viable approach to effectively manage weeds, pests, and improve overall soil quality, ultimately improving crop yields. Previous research to support these claims is lacking, but new scientific research may bring alternative insights into the BCSR philosophy and will help university professionals better assist growers and other clientele about the merits and drawbacks of soil balancing.

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