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Base cation saturation ratios vs. sufficiency level of nutrients: A false dichotomy in practice

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Abstract

Base cation saturation ratio (BCSR) or "soil balancing" is a soil management philosophy which strives to maintain targeted base cation saturation percentages in soil. Despite lack of Land Grant University (LGU) endorsement for decades, BCSR is widely practiced by many farmers in the United States, particularly in the organic farming community. Here, we explore BCSR persistence and present a framework around BCSR that reflects how it is conceived and practiced on working farms, with a key premise that BCSR practitioners typically use both LGU-endorsed sufficiency level of available nutrients (SLAN) and BCSR in a hybrid approach. Drawing on (a) a survey of LGU soil fertility scientists' perspectives on BCSR, (b) decades of published literature on impacts of lime and gypsum application, (c) soil test data from organic corn fields in a four-state region of the Midwest, and (d) a large state-wide soil test dataset from Ohio, we examined and tested five unique hypotheses about BCSR. We provide evidence to support the following statements: (a) published peer-reviewed literature on BCSR is limited and dated, (b) there is widespread agreement among soil fertility scientists that BCSR is not a legitimate practice of soil management, (c) studies of lime and gypsum application on soils can lend insight into the efficacy of BCSR, and (d) in many soils, managing soil acidity will also balance soils in BCSR ideal saturation percentages. Collectively, we summarize key findings from our interdisciplinary effort to provide an updated overview and a more nuanced perspective of BCSR in practice.

1 | INTRODUCTION

Base cation saturation ratio (BCSR) or "soil balancing" is a soil management philosophy which strives to maintain targeted base cation saturation percentages in soil, typically 60–75% calcium (Ca), 10–20% magnesium (Mg), 3–5% potassium (K), and 15% of other cations. The concepts of BCSR emerged in the late 1800s, but today are widely credited to William Albrecht, a soil scientist at the University of Missouri (Chaganti & Culman, 2017; Kopittke & Menzies, 2007). Albrecht was a highly regarded soil scientist throughout his career, who served as both department chair, and Soil Science Society of America president. He published a series of

Abbreviations: BCSR, base cation saturation ratio; CEC, cation exchange capacity; LGU, Land Grant University; SLAN, sufficiency level of available nutrients; SOC, soil organic carbon books, the *Albrecht Papers*, which laid the foundation for the concepts of BCSR. Ideas around BCSR have been more recently advanced and popularized by a variety of key agriculture consultants and organizations, most of whom are affiliated with ACRES (e.g., Midwestern BioAg and AgriDynamics; Ingram, 2007). These organizations devote much attention to managing soil Ca and Mg levels, and typically recommend applying high-Ca (low Mg) lime and gypsum to increase soil Ca base saturation levels and decrease Mg levels to optimize the functioning of soils.

The BCSR concept is widely practiced by farmers in the United States, particularly in the organic farming community. In a recent survey of all organic corn farmers in Indiana, Michigan, Ohio, and Pennsylvania, more than half of the respondents (859, 57.4% response rate) described using a BCSR approach (Brock, Jackson-Smith, Kumarappan, et al., 2021). However, BCSR concepts are not limited to organic farmers. Many commercial soil testing laboratory reports feature base saturation percentages of Ca, Mg, and K, and reports commonly contain ratios of Ca/Mg saturation percentages (i.e., Ca/Mg ratios). A number of labs provide some support and information around BCSR. For example, Brookside Consulting Inc. (New Bremen, OH) has more than 200 consultants, most of who subscribe to the concepts of BCSR and work with more than 2.6 million hectares (6.5 million acres) ofcrops or turf around the world (https://www.blinc.com/).

Scientific research on BCSR originated more than a century ago, but there have been minimal reports in peer reviewed literature (Kopittke & Menzies, 2007). A recent review by Chaganti and Culman (2017) reported only 15 published, peer-reviewed studies between 1930 and 2008 in the primary literature. Of these, seven were field trials and eight were greenhouse pot studies and focused mainly on measurements of crop yield, tissue nutrient concentrations, and soil chemistry. There are also numerous other scientific reports, conference proceedings, gray literature and bulletins on BCSR that exist. Review of this body of research is consistent with the published primary literature in failing to document positive plant responses with manipulating soil Ca/Mg ratios in experimental field trials.

Scientists concluded from these studies that BCSR is generally a misguided approach to soil management with no credible evidence to justify its use (Kopittke & Menzies, 2007). Major soil textbooks (e.g., Havlin et al., 2013; Weil & Brady, 2016) devote little time to this concept, and the scientific community has not given much credence to BCSR as a method of managing soil fertility (Kopittke & Menzies, 2007). Instead, Land Grant University (LGU) soil scientists and agronomists have widely adopted the concept of sufficiency level of available nutrients (SLAN), where nutrient availability is assessed individually, based on established critical levels (Black, 1993). The SLAN approach, sometimes in conjunction with a complementary build-up and maintenance approach, forms the basis for all LGU fertilizer recommendations in the United States.

Core Ideas

- Base cation saturation ratio (BCSR) is a widely practiced soil management approach.
- The BCSR has persisted for decades without university endorsement.
- The BCSR peer-reviewed literature is scant, mostly from studies conducted decades ago.
- The BCSR practitioners use both BCSR and sufficiency level of nutrients approaches.
- Managing soil acidity will commonly 'balance' many soils in a BCSR framework.

While previous scientific research tends to frame BCSR ratios as a competing universal theory to the predominant traditional SLAN approach, this portrayal paints a false dichotomy that does not reflect the lived complexities around the practice. Recent work by Brock, Jackson-Smith, Culman, et al. (2021) and Brock, Jackson-Smith, Kumarappan, et al. (2021) based on interviewing BCSR practitioners, reported a disconnect between the science and practice of BCSR. Several important themes emerged from this work including, (a) most BCSR practitioners in organic systems view BCSR not as a central tenet to soil management that is at odds with SLAN, but as one of many practices to manage soil fertility and build soil health, (b) practitioners describe multifaceted benefits to BCSR with a particular emphasis on positive changes in physical structure, and (c) BCSR management approaches can vary by soil type as most practitioners recognize the limitations of BCSR on sandier soils with low cation exchange capacity (CEC).

Most practitioners do not view BCSR as the central and sole guiding principle for soil management, but rather as one tool in a large toolbox to build soil health. Organic farmers who practice BCSR are also more likely to utilize a wide variety of soil amendments including high-Ca lime and/or gypsum, but also NPK fertilizers, micronutrients, microbial stimulants, and inoculants than other organic farmers (Brock, Jackson-Smith, Kumarappan, et al., 2021). In addition to purchased inputs, BCSR practitioners often emphasize the importance of management practices such as cover cropping, crop diversity, and the use of manure to optimize soil health (Brock, Jackson-Smith, Culman, et al., 2021).

While the effectiveness of BCSR has primarily been studied by soil fertility specialists through impacts on yield and plant nutrition, practitioners attest to a variety of other benefits from BCSR, particularly improvements in soil structure. Practitioners often agree that the central goal of BCSR is to improve soil structure which in turn increases the crop's ability to acquire nutrients (Brunetti 2014; Kinsey & Walters, 2006; Zimmer & Zimmer-Durand 2017). Manipulation of BCSR to improve soil structure is particularly focused on reducing Mg levels, sometimes more so than increasing Ca levels. In other words, Ca replaces Mg on exchangeable sites through mass flow after application of high-Ca amendments. This can be problematic on low CEC soils, as reductions in exchangeable Mg can cause Mg deficiencies (e.g., Leiva Soto, 2018; Rehm, 1994). Universally, practitioners we interviewed described soils with high Mg levels as "tight" and that achieving an ideal Ca/Mg ratio has a central role in "loosening" soils to a "flocculated" state (Brock, Jackson-Smith, Culman, et al., 2021). The length of time to see detectable impacts is an important consideration here, as changes in soil chemistry can occur within the year of application, whereas changes to soil physical properties can take years to decades to be realized (Nunes et al., 2020).

Soil scientists have often criticized BCSR as not appropriate for sandy soils (e.g., McClean, 1977; Rehm, 1994), but in our experience there is widespread acknowledgment by BCSR practitioners of the limitations of applying this framework on low CEC soils, taking into account local soil characteristics and farm management histories (Brock, Jackson-Smith, Culman, et al., 2021; Kinsey & Walters, 2006; Zimmer & Zimmer-Durand, 2017). Practitioners often state that soils with low CEC may not be good candidates for a BCSR approach. Opinions vary among practitioners, but low CEC soils not suitable for BCSR have been defined by some as ≤8 $cmol_c\ kg^{-1}$ (McKibben, 2012).

In this paper, our main goal is to present a framework around BCSR that is more reflective of how it is conceived and practiced on working farms. A key premise is that LGU soil scientists and agronomists too often conceptualize BCSR as both a dichotomous and mutually exclusive soil management philosophy relative to SLAN. We believe this is a generally misguided conceptualization and that virtually all practitioners of BCSR actually use a hybrid of SLAN and BCSR approaches. Moreover, recent work from our interdisciplinary team has provided new insights that help explain why BCSR practices continue to persist for decades without LGU endorsement (Brock, Jackson-Smith, Culman, et al., 2021; Brock, Jackson-Smith, Kumarappan, et al., 2021). To address and highlight these new insights, we will examine and test the following hypotheses:

1. H1: Publication bias is a significant driver of the lack of published BCSR studies in primary literature.
2. H2: There is widespread agreement among soil fertility scientists at LGUs that BCSR is not a legitimate practice of soil management.
3. H3: Despite the relatively few publications on BCSR, there is a large body of work reporting the effects of lime and gypsum application on soils that can lend insight into the efficacy of BCSR.
4. H4: Soil test values will differ between soils managed by farmers subscribing to BCSR vs. those that do not.
5. H5: BCSR guidelines often produce recommendations similar to those of LGU based on a SLAN framework. In many soils, managing soil acidity will also balance soils in BCSR ideal saturation percentages.

This is one of three related papers in this issue that explores the efficacy of BCSR soil management in a context that better reflects the attitudes, practices, and experiences of organic farmers who actively manage their soils using BCSR principles. In this paper, we summarize key findings that we believe will provide agronomists and research scientists a more nuanced perspective of BCSR. Companion papers that follow report results of field studies that document the effects of BCSR on (a) soil health properties and crop productivity (Chaganti et al., 2021) and (b) soil health in organic corn fields across four eastern Corn Belt states (Sprunger et al., 2021).

2 | METHODS AND MATERIALS

2.1 | Survey of soil fertility scientists

We constructed a targeted survey of state soil fertility scientists at LGUs with the following goals: (a) to ask about their perceptions and attitudes of BCSR, (b) identify how many state fertility specialists have conducted research on BCSR, and (c) document evidence of publication bias with BCSR research (lack of publishing due to no observed significant effects). We identified a total of 105 soil fertility scientists from LGU websites across the United States. In the spring of 2017, these specialists were emailed and invited to complete a Qualtrics survey (see Supplementary Materials for the survey questionnaire), with an email reminder 1 wk later. Fifty-one people responded to the survey (a 45.5% response rate), and 32 provided additional written comments.

2.2 | Organic corn farmer soil test data

In the spring of 2018, Brock, Jackson-Smith, Kumarappan, et al. (2021) created and mailed a survey to all 1,662 certified organic corn farmers listed in the USDA certified Organic INTEGRITY Database in four states: Indiana, Michigan, Ohio, and Pennsylvania. The survey contained diverse questions about farm operations, crop yields, and economics and overall philosophical approaches to organic soil management, including the use of "BCSR" and "soil balancing" practices. Survey respondents were able to opt-in for a free soil health test. A total of 455 farmers indicated they were interested and were mailed a package that included soil sampling instructions, materials, pre-paid return postage. We received 195 soil samples (42.9% response rate) from 73 different counties across Michigan, Indiana, Ohio, and Pennsylvania. These soil samples had a routine soil nutrient analysis following the procedures outlined and recommended by LGUs in the north- central region (NCERA-13, 2015). Soil water pH was measured with a glass electrode in a 1:1 soil/water (w/v) mixture (Peters et al., 2012) and extractable soil Ca, Mg, and K were determined using the Mehlich-3 extractant (Mehlich, 1984) and analyzed with an inductively coupled plasma spectrometer. Cation exchange capacity was estimated by summation of cations (Warncke & Brown, 2015), by first converting Mehlich-3 (M3) base cation concentrations to equivalent ammonium acetate concentrations for Ca (M3-Ca × 0.75), Mg (M3-Mg × 0.88), and K (M3-K × 0.84), then summing cations as reported here: https://spectrumanalytic.com/support/library/ff/CEC_BpH_and_percent_sat.htm. This correction was developed by Spectrum Analytic to keep estimated CEC values consistent, regardless of the extractant used (ammonium acetate or Mehlich-3). We have independently verified that Mehlich-3 extracts proportionally more base cations than ammonium acetate (Culman, Mann, et al., 2020), which would slightly over-estimate CEC values without this correction. Soils were also analyzed for three measurements of active organic matter (permanganate-oxidizable carbon (POXC), mineralizable carbon and autoclaved-citrate extractable (ACE) soil protein), with more details provided by Sprunger et al. (2021). Soil test data from the organic farm survey were analyzed via ANOVA to determine differences in soil properties due to subscription to BCSR (Yes/No). Analysis of variance was conducted in R (R Core Team, 2020) using the *agricola* package with significant differences determined at $\alpha = .10$.

2.3 | Ohio statewide soil test data

In the spring of 2016, we approached a major commercial soil testing laboratory in Ohio, Spectrum Analytic Inc. (Washington Courthouse, OH), and requested anonymous soil test data from Ohio for the past 4 yr (2012–2015) on the same routine soil nutrient analyses described above. Identifying information was removed and the soil test data reflecting 342,840 samples were shared. Since we were only interested in mineral soils, we filtered out observations with CECs >30 $cmol_c\ kg^{-1}$. This provided data from 335,647 soil samples over 4 yr. Statewide soil test data were classified into three pH ranges: low (<6.0), optimal (6.0–6.8), and high (>6.8), and distributions were visualized with the *geom_density* function in the *ggplot* package in R.

3 | RESULTS AND DISCUSSION

H1: Publication bias is a significant driver of the lack of published BCSR studies in primary literature.

H2. There is widespread agreement among soil fertility scientists at LGUs that BCSR is not a legitimate practice of soil management.

We surveyed LGU soil fertility scientists to better understand attitudes about BCSR and to document any evidence of publication bias, that is, lack of published content due to no significant effects observed. Out of the 51 total respondents (45.5% survey response rate), only six scientists reported having ever conducted BCSR research and only two of the six had published their work in peer-reviewed journals. When asked for names of colleagues who have conducted BCSR research, the majority of respondents (32 out of 51) could not (or did not) list any names. Those respondents who provided specific names of colleagues mostly listed emeriti professors or deceased scientists (14 of 19 respondents). These responses suggest that the vast majority of active soil fertility or chemistry professors across the United States have not conducted any research on BCSR, and that publication bias has played a limited role in the recent past but may have played a larger role several decades ago when BCSR was a more active area of research.

When asked about their attitudes toward BCSR, the majority of respondents (78.0%) agreed that "There is no scientific merit to this approach (BCSR), and this has been shown repeatedly" (Figure 1). Not a single respondent disagreed with this statement. However, agreement with the statement, "I have not seen enough evidence to either endorse or discredit this approach" generated less consistent results, as only half of the respondents (54.0%) disagreed with this statement and 36% agreed. These results again likely reflect the length of time that has passed since any significant research has been conducted on BCSR and the lack of institutional memory of specific studies.

Less than a quarter (21.6%) of the respondents agreed with the statement, "It is possible that farmers do see benefits from this approach," again demonstrating their skepticism of BCSR (Figure 1). When provided the opportunity to give open-ended comments, 32 respondents provided feedback on a diversity of topics. Twenty-five percent of the comments suggested that the private sector was influencing farmers to waste money on unnecessary amendments and 25% of the comments related to the fact that there was no ideal soil Ca/Mg ratio for plants, while 19% noted that attention to this ratio only matters with extreme soil cation imbalance or on unusual soil types. Together these comments demonstrate a largely consistent view that BCSR is an unjustified and unproven practice. Some survey respondents lamented how the lack of demonstrated efficacy of BCSR has not deterred it from being

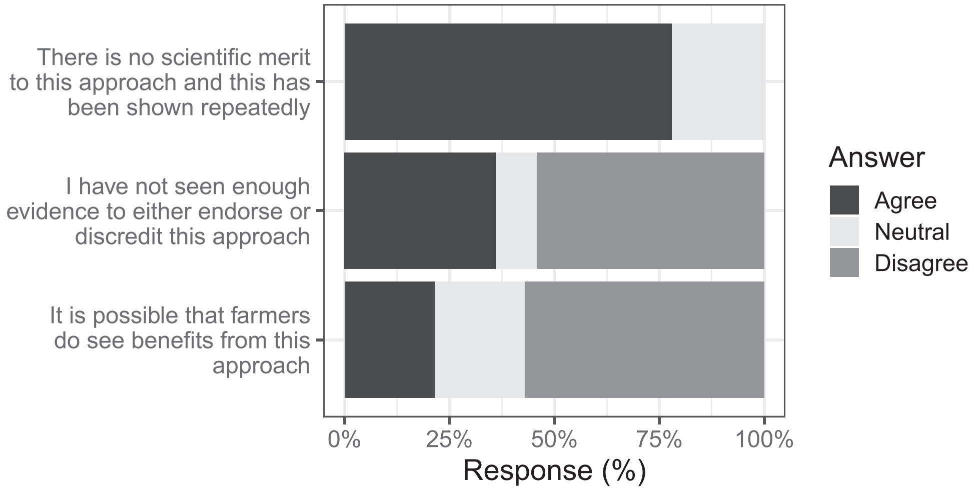

FIGURE 1 Land Grant University soil fertility scientists' views on base cation saturation ratio (BCSR)

practiced, as one respondent noted "you cannot refute religion with science" and another referenced BCSR as "popular modern soil alchemy" (Brock, Jackson-Smith, Culman, et al., 2021).

H3. Despite the relatively few publications on BCSR, there is a large body of work reporting effects of lime and gypsum application on soils that can lend insight into the efficacy of BCSR.

The lack of reported research manipulating Ca/Mg ratios (Kopittke & Menzies, 2007; Chaganti & Culman, 2017) does not equate to a total lack of knowledge on the subject. For example, there is a large body of literature reporting on the effects of lime and gypsum on soil, crop, and environmental properties (Figure 2). High-Ca lime (low Mg content) and gypsum are the two primary amendments that BCSR practitioners use to manipulate soil Ca/Mg ratios. High-Ca lime is applied to fields with low soil pH, and gypsum when soil pH is optimal but Ca/Mg are not. Applying agricultural lime to adjust pH results in two outcomes: (a) reducing neutralizable (exchangeable) acidity and raising soil pH, (b) increasing Ca saturation percentages (Figure 2). We questioned whether scientists and BCSR practitioners may, at times, attribute the positive benefits of liming soils to different phenomena. That is, if scientists attribute positive effects of lime solely to increases in pH and BCSR practitioners attribute it to increases in Ca saturation percentages.

The benefits of lime on crops are well-established and non-disputed among scientists (e.g., Haynes & Naidu, 1998; Li et al., 2019). However, the benefits of gypsum have been less consistent and more site-specific. Gypsum benefits have been recently reviewed (Zoca & Penn, 2017), with studies reporting the effects of gypsum application on crop yields and tissue concentrations (e.g., Bullock &Goodrоad, 1989; Caires et al., 2011; Chaganti et al., 2019; Kim, et al., 2013; Michalovicz et al., 2014; Nora, Amado, Nicoloso, Gruhn, 2017; O'Leary & Rehm, 1990; Pagani & Echeverría, 2011; Steinke et al., 2015; Watts & Dick, 2014), soil hydrology and nutrient losses (e.g., Dontsova & Norton, 2002; Favaretto et al., 2006; Jayawardane & Blackwell, 1986; King et al., 2016; Tirado-Corbalá et al., 2013), and soil aggregation and physical structure (e.g., Buckley & Wolkowski, 2014; Ellington, 1986; Presley et al., 2018; Tirado-Corbalá et al., 2019).

There are a number of mechanistic effects that gypsum can have on soil, both direct and indirect, due to Ca and S (Figure 2). It is widely acknowledged that gypsum is an effective tool for remediating sodic soils and for improving soil conditions on acidic, weathered soils with high levels of soluble aluminum (e.g., Pias et al., 2020; Wamono et al., 2016). However, numerous studies report conflicting effects of gypsum application on non-sodic and younger soils, particularly those in the Midwest. For example, recent work has demonstrated more consistent positive effects of gypsum application in acidic, weathered soils in Brazil and Paraguay (Bossolani et al., 2020; Caires et al., 2011; Nora & Amado, 2013; Carmeis Filho et al., 2017; Nora, Amado, Nicoloso, Mazuco, et al., 2017; Pias et al., 2020; Pott et al., 2020) relative to 10 diverse soils from the United States (Kost et al., 2018). Soil C storage has been shown to be positively affected by higher base saturation and Ca availability in tropical and weathered soils. For example, de Oliveira Ferreira et al. (2018) showed that soil management practices that promote Ca saturation can increase soil organic carbon (SOC) recovery in oxisol soils under long-term no-till conditions. Similar increases in SOC were also reported by Filho et al. (2017) under high Ca saturations achieved either through lime or gypsum applications or a combination of both. Furthermore, Bonini Pires et al. (2020) also reported improved microbial biomass activity under higher Ca saturation conditions along with crop diversification.

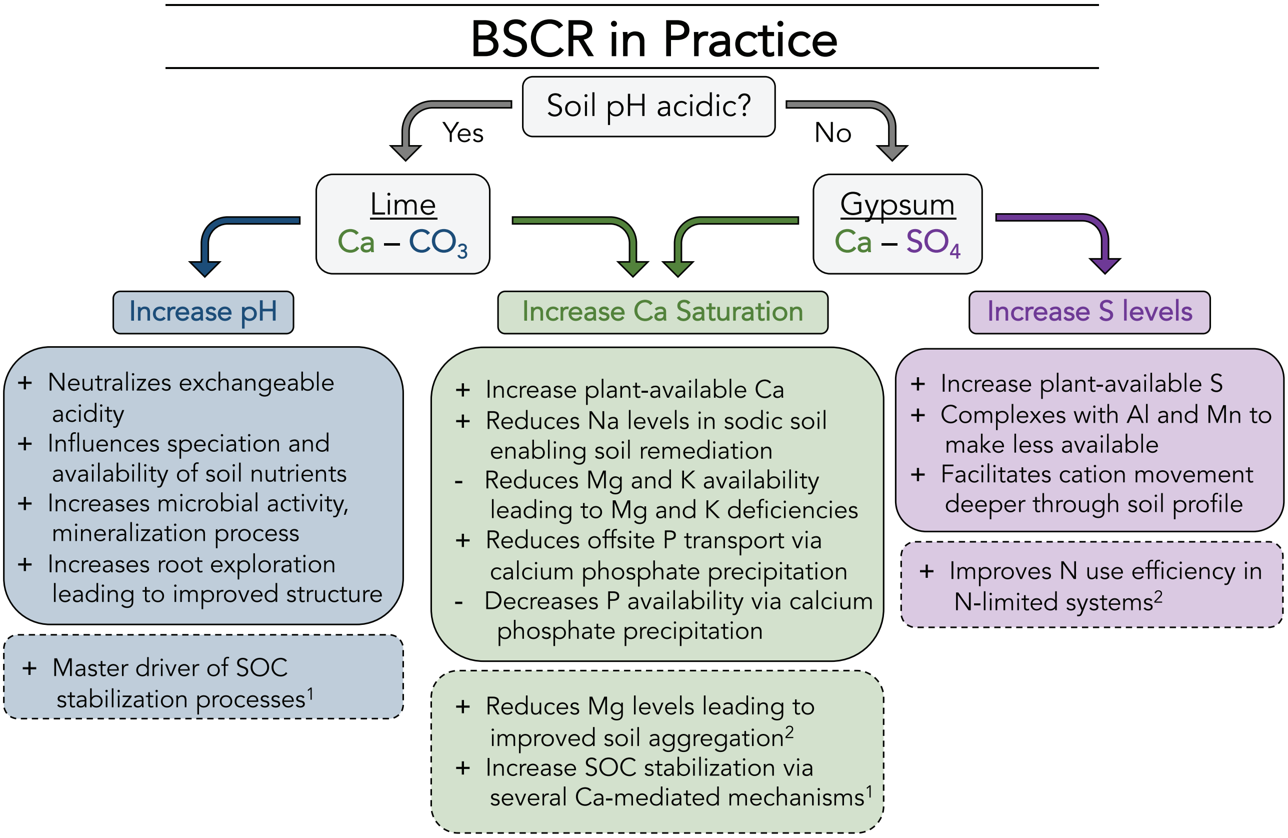

FIGURE 2 Generalization of how base cation saturation ratio (BCSR) is practiced. Soil pH determines if practitioners apply high-calcium (Ca) lime or gypsum, the two primary tools for increasing Ca and decreasing Mg saturation percentages. Lime and gypsum have potential positive (+) and negative (–) impacts on soil properties and plant production, due to three primary mechanisms, (a) increasing pH, (b) increasing Ca saturation or (c) increasing sulfur (S) levels. Established mechanisms are listed in the above boxes with solid lines, while less understood or inconsistent mechanisms are listed below in boxes with dashed lines. Less understood mechanisms are discussed in more detail in the reviews Rowley et al., 2018[1] and Zoca & Penn, 2017[2]

Gypsum is applied to soil to achieve numerous outcomes (Figure 2) and site-specific factors often dictate the efficacy of the application. Of particular importance to BCSR practitioners is the impact of using Ca to displace Mg from exchange sites to improve soil aggregation and physical structure (see Chaganti & Culman, 2017 for in-depth discussion). Using Ca to replace Mg on exchange sites is a fundamental tenet of BCSR practitioners (Brock, Jackson-Smith, Kumarappan, et al., 2021) and has scientific merit, but has not been robustly demonstrated in empirical field experiments to date (Chaganti & Culman, 2017; Chaganti et al., 2021). Future research is needed to better understand how soil type, clay mineralogy, and management practices influence crop and soil responses observed with increasing Ca saturation percentages and the relative roles specific cations (e.g., Ca vs. Mg) play in these responses.

H4. Soil test values will differ between soils managed by farmers subscribing to BCSR vs. those that do not.

We analyzed 195 soil samples from certified organic farms that grew organic corn in 73 different counties across MI, IN, OH, and PA. The soil samples represented a diversity of organic farms, soils, and management practices. Complete details of the study and results are reported in Sprunger et al. (2021). Of the 195 soil samples received and analyzed, 58% of these farms said they subscribe to and practice BCSR. We examined differences in key soil parameters that should be most influenced by BCSR management, namely, soil pH, base cation saturation percentages, and soil Ca/Mg ratios. Analysis of variance indicated no significant differences ($P > .10$) in any of these measured properties between those who did or did not subscribe to BCSR. Distributions of these soil properties by group reveal no discernible trends (Figure 3), suggesting that BCSR management by organic corn farmers is not readily detected in soil test results alone. We, therefore, reject our hypothesis that subscription to BCSR drives differences in soil test values. These results highlight the complexity and variability encountered across these organic farms (see Brock, Jackson-Smith, Culman, et al., 2021; Sprunger et al., 2021), reflect the fact that soils are highly buffered, and suggest that extractable soil Ca and Mg test values are difficult to change, even when farmers intend to modify these levels.

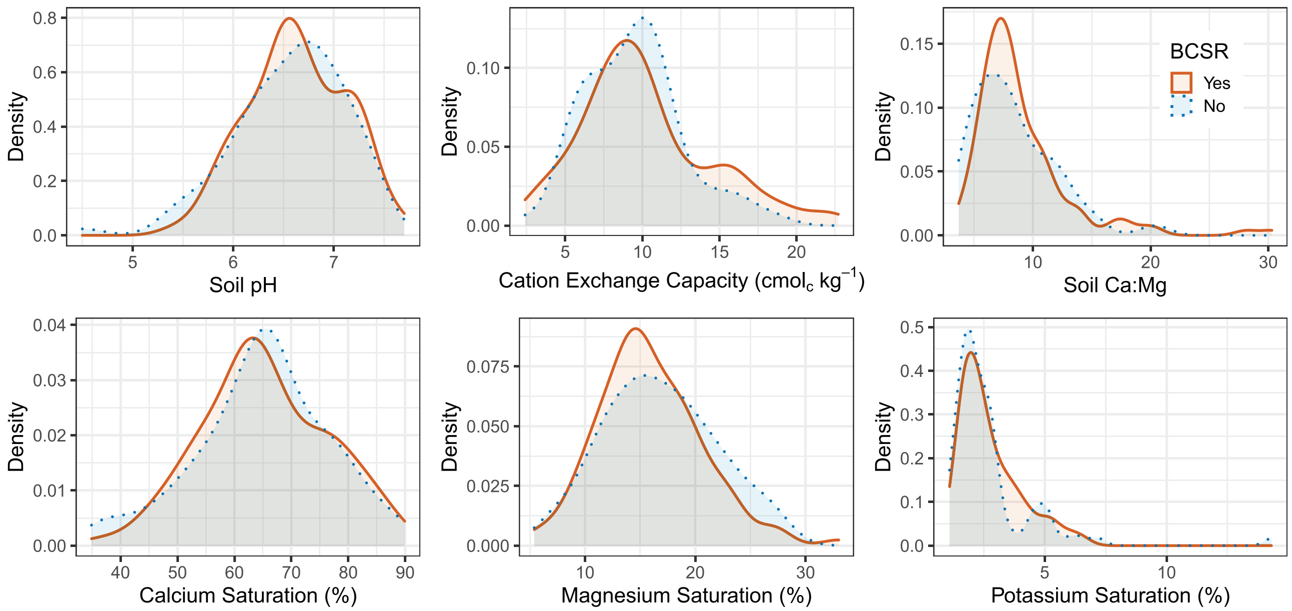

FIGURE 3 Distributions of soil properties from organic corn farms (n = 195) based on farmer subscription to base cation saturation ratios (BCSR, red solid line) or not (blue dotted line)

H5. BCSR guidelines often produce recommendations similar to those of LGU based on a SLAN framework. In many soils, managing soil acidity will also balance soils in BCSR ideal saturation percentages.

A key consideration when comparing BCSR to SLAN is the management of soil acidity. We examined 4 yr of Ohio soil test data results from a major commercial soil testing laboratory. We focused on mineral soils (CECs <30 cmol$_c$ kg^{-1}) and classified them into three pH classes for agronomic field crop production in Ohio: low (<6.0), optimal (6.0–6.8), and high (>6.8), reflecting 82,532, 171,820, and 81,295 soil samples respectively. The distributions of these data suggest that soils with low soil pH have much lower Ca saturation percentages relative to soils with optimal pH (Figure 4). Interestingly, soils classified as either optimal or high pH have a large percentage of observations above 75% Ca saturation, the Albrecht BCSR upper limit.

Magnesium saturation percentages show an opposite trend, where soils classified as low pH have generally lower distributions that are more closely aligned with Albrecht ideal ranges (10–20%) relative to soils with optimal or high pH (Figure 4). Soil potassium saturation distributions across the three pH classifications exhibit much more similarities than Ca or Mg saturation distributions. These results indicate that when soils are managed to be in optimal pH range for field crop production, they often fall within the BCSR ideal ranges for Ca and K, but not for Mg. While we used strict criteria here (black vertical lines in Figure 4), nearly all BCSR practitioners we interviewed do not adhere to the rigid saturation ranges and make adjustments depending on site-specific factors (Brock, Jackson-Smith, Culman, et al., 2021). Regard-

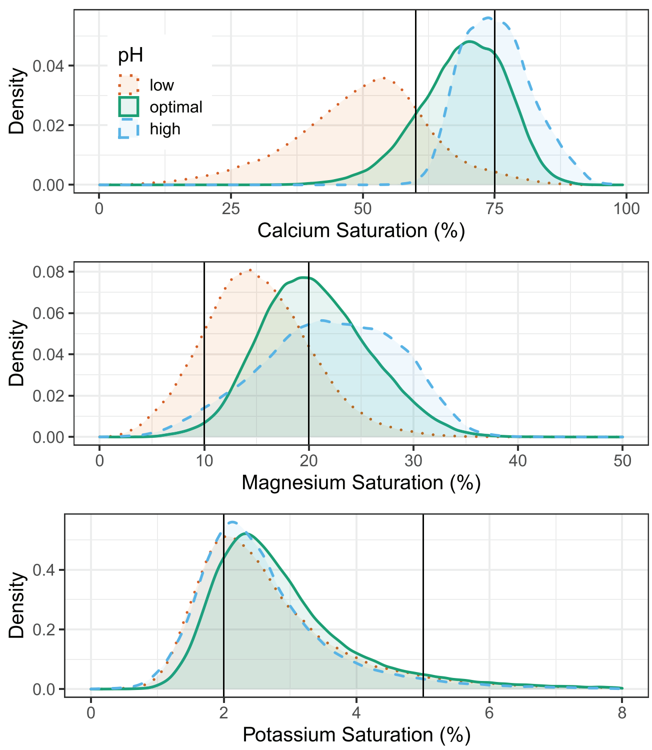

FIGURE 4 Distributions of calcium, magnesium, and potassium base saturation percentages by soil pH, defined as low = < 6.0 (red, dashed line), optimal = 6.0–6.8 (green, solid line), and high = > 6.8 (blue, long dashed line). Albrecht base cation saturation ratios (BCSR) ideal saturation ranges are denoted by black vertical lines: 60–75% for Ca, 10–20% for Mg, 2–5% for K. Data are from a major commercial soil testing laboratory and represent all Ohio soil samples with cation exchange capacities <30 cmol$_c$ kg^{-1} analyzed by Mehlich-3 between 2012 and 2015 (n = 335,647)

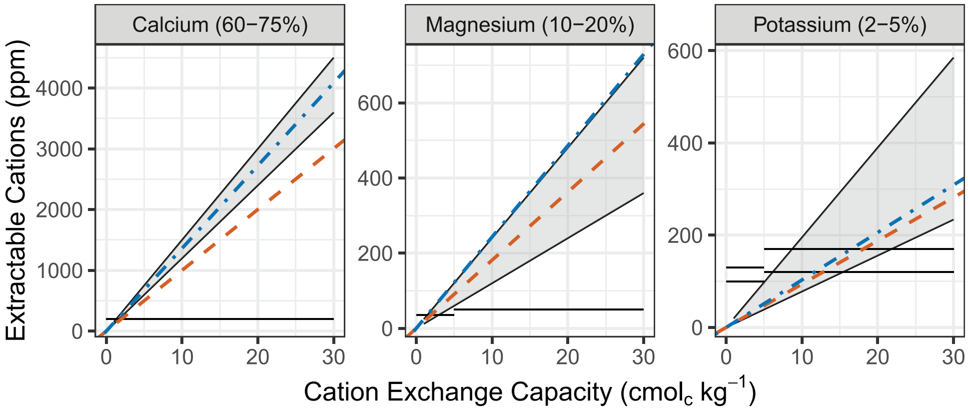

FIGURE 5 Relationship between Ohio sufficiency level of available nutrients (SLAN) soil test recommendations for calcium, magnesium, and potassium (horizontal black solid lines) and base cation saturation ratio (BCSR) ideal ranges (gray ribbons) as a function of cation exchange capacity (CEC). The slanted dashed lines represent the best fit regression line for Ohio soils (n = 335,647) that were classified as optimal pH (blue dot-dashed lines, 6.0–6.8) or below optimal (red dashed lines, <6.0)

less, our hypothesis that soils with optimal soil pH would have cation saturations mostly aligned with BCSR ideal ranges is plausible for Ca and K but is rejected when considering Mg saturation percentages. The majority of lime sold in Ohio is dolomitic (high-Mg lime; Ohio Department of Agriculture, 2020), likely resulting in the increased Mg saturations with optimal pH soils, and why BCSR practitioners routinely recommend high-Ca lime over dolomitic lime.

Finally, we wanted to examine the relationship between LGU fertilizer recommendations based on a SLAN and BCSR approach to evaluate how different these approaches might be. We used the field crop fertilizer recommendations for Indiana, Michigan, and Ohio (Culman, Fulford, et al., 2020) and compared the recommended minimal Mehlich-3 extractable values (i.e., critical levels with SLAN) for Ca, Mg, and K. We regressed recommended critical soil test levels (black solid horizontal lines) vs. CEC and included ideal BCSR ranges (gray ribbons) for soils with a neutral pH (Figure 5). We then used the large Ohio soil dataset described above (Figure 4) and regressed a best fit line for Mehlich-3 extractable levels by CEC for each nutrient, based on soils with optimal pH (blue dot-dashed line, 6.0–6.8) and low pH (red dashed line, <6.0). When considering only recommended SLAN levels (horizontal black lines) and the BCSR ideal ranges (gray ribbons), there appears to be a substantial difference between these two approaches (Figure 5). For example, at higher CEC values, it is conceivable that following BCSR would require application of more product than is necessary to meet critical levels required by SLAN. This could result in over-applications of Ca, Mg, and/or K amendments to increase exchangeable cation levels and substantially reduce farmer profitability and return-on-investment, a main criticism presented by others in the past (e.g., McLean et al., 1983; Olson et al., 1982). Conversely, BCSR practitioners could argue that critical levels based on a SLAN approach could greatly underestimate required levels for optimal soil management. However, the differences between these two approaches are not as disparate as they appear on the surface.

When one considers the Ohio soil test data within optimal pH (blue dot-dashed lines), average soil test values fall within the ideal BCSR range for Ca and K, and are on the upper limit for Mg. While these best fit regression lines represent only the "average" soil test values and not the full distribution around these lines (Figure 4), these data suggest that in many instances, a soil that has been managed for optimal pH may fall within an ideal BCSR range. These data also justify the preference of high-Ca lime over dolomitic lime for BCSR practitioners, as soils with optimal pH levels have higher Mg saturation percentages on average than those soils with <6.0 pH. Since the majority of lime sold and applied in Ohio is dolomitic lime, managing soils to increase Ca saturation and lower Mg saturation logically necessitates high-Ca lime.

Despite the above noted similarities between BCSR and SLAN, we should be clear that BCSR and SLAN are in fact, very different conceptual approaches to soil management. Our intention here is not to suggest otherwise, but rather provide evidence that there can be considerable overlap in soil test level outcomes if the soil is managed for optimal pH, regardless if a practitioner is following BCSR or SLAN based on LGU recommendations. Recognition of this phenomenon may help explain the persistence of BCSR practice without LGU endorsement for more than 40 yr.

4 | CONCLUSIONS

Our work suggests that publication bias has played a limited role in the past several decades, as few soil fertility specialists have engaged in BCSR research (H1 rejected). There is however a consensus among soil fertility scientists at LGUs that BCSR is not a legitimate practice of soil management (H2 accepted). Even though published research on BCSR is scant, there is a rich body of literature on lime and gypsum that can lend insight into the efficacy of BCSR and when any positive effects may or may not be observed (H3 accepted). Additional research is needed to better understand the relative roles that Ca vs. Mg play in SOC stabilization processes as well as the role that S plays in nitrogen (N)-limited environments, commonly experienced in organic cropping systems. Our findings suggest that differences in farmer subscription to BCSR were not detectable in soil test data from their fields (H4 rejected), but that managing soil acidity will also balance soils in BCSR ideal saturation percentages (H5 accepted).

Recent work by our team has noted the disconnect between science and the practice of BCSR, with scientists generally conceptualizing BCSR practices as dichotomous to SLAN (Brock, Jackson-Smith, Culman, et al., 2021; Brock, Jackson-Smith, Kumarappan, et al., 2021). In practice, BCSR practitioners consider and use SLAN, along with a broad array of soil health building management practices, describing multiple benefits from this approach, particularly improvements in soil physical structure. This more nuanced understanding was developed from an interdisciplinary effort that intentionally engaged BCSR practitioners at the early stages through mixed methods of interview and survey work in social sciences, which then informed on-station and on-farm field experimentation in agronomy and soil sciences.

The practice of BCSR is just one example where the approaches of scientists and farmers diverge, and these gaps have isolated LGU scientists and extension educators from the farming communities they intend to serve. In fact, BCSR could provide a model case study as to how divergent views on soil science have contributed to independent and non-overlapping information channels in different farming communities. Our research on BCSR raises many important questions about how farmers learn, where they turn for information and how they validate truths. Although outside the scope of this journal, these are critical questions that extension professionals and scientists should contemplate in the name of more effective applied agronomic outreach. A number of LGU scientists we surveyed lamented that BCSR practitioners seem to dismiss results of scientific studies over the decades. Meanwhile, BCSR practitioners dismiss much of the scientific research on BCSR as being outdated and based on a mischaracterization of their approaches or practices. This impasse will continue for decades to come if efforts are not made to better engage scientists with BCSR practitioners. With the increased interest in soil health among both scientists and growers, we believe numerous opportunities exist for interdisciplinary research teams to co-learn through participatory research with farmers, particularly on historically divisive issues.

SUPPLEMENTAL MATERIAL

The targeted survey of state soil fertility scientists at Land Grant Universities asking about attitudes and previous research experiences with BSCR.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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