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Base cation saturation ratios, soil health, and yield in organic field crops

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Abstract
Base cation saturation ratio (BCSR) is a soil management philosophy that postulates having an ideal ratio of base cations for maximizing crop yields. This practice is widely used on organic farms, and BCSR practitioners commonly describe improvements in soil health and crop productivity. However, studies evaluating the efficacy of BCSR on soil biological and physical properties are lacking. This 6-yr field study evaluated the effects of changing soil calcium/magnesium (Ca/Mg) ratios on organic corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields and comprehensive soil health properties at two sites in Ohio with contrasting soils. Three soil amendments—(a) control, (b) gypsum (calcium sulfate), and (c) epsom (magnesium sulfate)—were applied to drive soil Ca and Mg levels in opposite directions. Amendment application resulted in soil Ca/Mg ratios 1.6 and 2.5 times higher in gypsum soils relative to epsom soils. Soil biological health, measured by permanganate oxidizable carbon, mineralizable carbon, and soil protein, was not affected by either gypsum or epsom applications. Likewise, soil physical quality measured by aggregate stability, infiltration, and penetration resistance was not significantly affected by gypsum or epsom additions at either site. Amendment application did not affect crop yields and there was no significant relationship between crop yields and the range of soil Ca/Mg ratios. Results from this study do not provide any evidence that BCSR improves soil health and organic field crop productivity.

1 | INTRODUCTION

Base cation saturation ratio (BCSR) is a soil management approach that strives to achieve targeted percentages of exchangeable soil calcium (Ca), magnesium (Mg), and potassium (K). The development of BCSR theory dates back more than 100 yr when Loew first proposed the concept of an optimal Ca/Mg ratio in soil (Loew, 1892). Work by Bear and col-

leagues (Bear & Toth, 1948; Bear et al., 1945) on Ca/Mg ratios influenced Albrecht (1975) and Graham (1959), which finally led Albrecht to conclude that a balanced soil should have 60–75% Ca, 10–20% Mg, and 2–5% K to maximize crop yields. Today the core ideas of BCSR are widely credited to William Albrecht (Chaganti & Culman, 2017).

Studies have compared BCSR with widely established soil management philosophies, such as the sufficiency level of available nutrients (SLAN), where nutrient availability is assessed by individual elements (Black, 1993). These studies failed to find evidence to support the existence of an ideal

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Abbreviation: BCSR, base cation saturation ratio; MWD, mean weight diameter; POXC, permanganate oxidizable carbon; PR, penetration resistance.

soil base cation saturation percentage (Chaganti & Culman, 2017; Kopittke & Menzies, 2007). For example, Olson et al. (1982) compared corn (*Zea mays* L.) grain yields between different recommendation philosophies over an 8-yr period in Nebraska. These authors concluded that the BCSR approach, relative to SLAN, failed to improve yield and was more expensive due to additional amendment applications to alter Ca/Mg ratios. McLean et al. (1983) and Murdock (1992) also concluded that the BCSR approach was more expensive with no added yield advantage over SLAN. The collective result of these studies has led most soil scientists to disregard BCSR and view it as a misguided approach to soil management (Culman et al., 2021).

Despite the lack of evidence to support BCSR in the scientific literature, BCSR is widely practiced, particularly by organic farmers. In a recent survey, over half of organic farmers in Indiana, Michigan, Ohio, and Pennsylvania reported using BCSR (n = 859, 57.4% response rate; Brock, Jackson-Smith, Kumarappan, et al., 2021). Farmers reported practicing BCSR because they believe it improves crop performance, crop quality, soil health, and weed control. However, these beliefs are not held exclusively in the organic farming community. The practice of BCSR is commonly found in the crop consulting and turfgrass industries. For example, Brookside Consulting Inc. (New Bremen, OH) has a large network of over 200 consultants that widely practice BCSR, working with over 2.6 million ha of crops or turf around the world (https://www.blinc.com/). Likewise, numerous commercial soil testing laboratories report base cation saturations and Ca/Mg ratios on their soil test reports because clients often request this information.

In interviews and case studies, private crop consultants and farmers ascribed positive changes to soil physical, chemical, and biological properties while implementing BCSR practices (Brock, Jackson-Smith, Culman, et al., 2021; Jabbour et al., 2014; Zwickle et al., 2014). In particular, practitioners most often described improvements in soil physical structure with BCSR practices. A core concept here is that Mg makes soils "tight" and application of Ca (e.g., high-Ca lime and gypsum) helps flocculate and "loosen" soils. Another commonly echoed theme is the ability of BCSR practices to improve biological activity in soils, which in turn increases nutrient availability and crop quality (Brock, Jackson-Smith, Culman, et al., 2021). However, to date, there is limited information on the impacts of BCSR management on soil physical and biological properties, as nearly all previously published studies focused on the impact of BCSR on soil chemical properties and crop productivity (Chaganti & Culman, 2017).

Although claims of improved soil physical and biological function with BCSR management have yet to be substantiated in the literature, there is a theoretical and mechanistic basis for some of these assertions. For example, soil structure, including aggregate stability, governs important processes such as

Core Ideas

- Base cation saturation ratio (BCSR) is widely practiced by organic farmers.
- Efficacy of BCSR in organic systems has yet to be comprehensively evaluated.
- After 5 yr, BCSR had no impact on measured soil biological and physical properties.
- BCSR management and Ca/Mg ratios had no impact on corn or soybean yields.
- Our results corroborate other studies suggesting an ideal soil Ca/Mg ratio does not exist.

aeration, water infiltration, and ultimately plant growth (Bronick & Lal, 2005; Horn et al., 1994). The role of different cations in altering soil structure through their effects on soil aggregation is well known. Increasing soil exchangeable Ca can influence soil hydrology and drainage (King et al., 2016), by promoting better soil aggregation and improving water infiltration into the soil (Amézketa, 1999). Alternatively, studies have shown elevated Mg saturation on soil exchange sites can promote soil disaggregation through increased clay dispersion, leading to reduced soil water infiltration (Dontsova & Norton, 2002; Qadir et al., 2018; Zhu et al., 2019). Therefore, it is possible that Ca applications may lead to improved aggregation and related outcomes (Chaganti & Culman, 2017).

Likewise, Ca and pH play a strong role in influencing soil biological communities and processes. For example, the diversity and richness of soil bacterial communities are strongly influenced by soil pH (Fierer & Jackson, 2006), as are mineralization processes (Havlin et al., 2014), and soil Ca plays known mechanistic roles in soil organic carbon (C) stabilization (Rowley et al., 2018). These biologically mediated processes can be inferred through indicators of soil biological health, such as permanganate oxidizable C (POXC) (Weil et al., 2003), mineralizable C (Franzluebbers et al., 2000), and soil protein (Hurriso, Moebius-Clune, et al., 2018). These indicators represent the active and rapidly cycled pool of soil organic matter (SOM) and are often considered robust soil biological health indicators that are sensitive to changes in management (Culman et al., 2012; Hurisso et al., 2016; Roper et al., 2019).

With regard to BCSR management, some key questions remain unanswered, including (a) What specific role does Mg play in soil aggregation processes?, (b) What role does Ca relative to pH play in improvements of soil biological activity and health?, and (c) Are any soil improvements with BCSR able to translate into improved crop performance and yields? Disentangling the effects of pH and Ca remains an elusive task and was a major criticism of Albrecht's work that originally led to the formation of the BCSR philosophy (Kopittke &

Soil property	Hirzel	West Badger
Soil pH	6.9 ± 0.1	5.9 ± 0.1
Cation exchange capacity ($cmol_c$ kg^{-1})	21.8 ± 0.5	9.9 ± 0.3
Organic matter (g kg^{-1})	24.1 ± 2.2	13.9 ± 0.6
Calcium (mg kg^{-1})	3,601 ± 58	965 ± 24
Magnesium (mg kg^{-1})	476 ± 9	214 ± 12
Potassium (mg kg^{-1})	172 ± 8	97.0 ± 3
Ca Saturation (%)	68.5 ± 2.0	37.0 ± 2.1
Mg saturation (%)	16.1 ± 0.5	16.1 ± 1.2
K saturation (%)	1.7 ± 0.1	2.1 ± 0.1
Ca/Mg ratio	8.6 ± 0.2	4.6 ± 0.2

Menzies, 2007). Therefore, experimentation that specifically manipulates soil Ca/Mg ratios without concurrent changes in pH is needed to address these unanswered questions.

This study is the first to comprehensively evaluate the effect of BCSR on soil health, including physical, chemical, and biological parameters. A 6-year field study was conducted at two sites with contrasting soils with an overall goal to test the efficacy of BCSR in organic grain systems. The specific objectives were to evaluate the effects of BCSR on (a) soil physical, chemical, and biological health; and (b) organic grain crop productivity. The continued widespread practice of BCSR in organic systems, contrary to land-grant university recommendations, necessitated a thorough evaluation of this practice and impact on soils and crops.

2 | MATERIALS AND METHODS

2.1 | Site and experimental setup

Two field trials were established in 2015 at the Hirzel and West Badger sites in Ohio. Both sites experience humid continental climate with warm to hot summers and cold winters. The Hirzel site is located near the city of Bowling Green (Wood County) on a Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualf) at 41°27′24″ N, 83°39′50″ W. The West Badger site is located near Apple Creek (Wayne County) on a Canfield silt loam (fine-loamy, mixed, active, mesic Aquic Fragiudalf) at 40°46′54″N, 81°51′06″W. Hirzel and West Badger have been under certified organic production since 2004 and 1998, respectively, and were previously in agronomic grain and forage rotations. Baseline soil properties were measured across crop-replicate combinations in the spring 2015 before planting and amendment application (Table 1). Soil values reflected different starting points regarding BCSR management, as Hirzel had Ca and Mg

saturation values that would be considered relatively balanced (69 and 16%, respectively), while West Badger soils would be considered unbalanced (37 and 16%, respectively) (Table 1).

A split-plot randomized complete block design with four replications was imposed at both sites with crop as the main plot and amendment application as the subplot factor with three treatments: (a) epsom (magnesium sulfate, $MgSO_4.7H_2O$), (b) gypsum (calcium sulfate, $CaSO_4.2H_2O$), and (c) an untreated control. Experimental plots measured 4.6 m by 85 m at Hirzel and 6 m by 12 m at West Badger. Soil amendments were applied at Hirzel in spring and fall of 2015, spring 2017, summer 2019, and spring 2020. At West Badger, they were applied in spring and fall of 2015 and every spring from 2017 through 2020. Amendments were incorporated into the soil through moldboard plowing or chisel tillage depending on the year at both the sites. Amendment applications were based on the baseline Ca/Mg ratios and input from our stakeholder advisory committee consisting of farmers and crop consultants who were actively practicing BCSR. Gypsum was applied to increase Ca/Mg ratios, and epsom was applied to decrease Ca/Mg ratios. Over 6 yr (2015–2020), 11.8 and 12.3 Mg ha^{-1} of gypsum and 13.4 and 12.3 Mg ha^{-1} of epsom were applied cumulatively at Hirzel and West Badger, respectively. In addition to amendments, both sites received composted dairy manure before planting crops in some years. Compost was applied to all plots at 5 Mg ha^{-1} at the Hirzel site only in 2015. Plots planted to corn and soybean [*Glycine max* (L.) Merr.] at West Badger received compost at rates of 38, 22, 7, and 26 Mg ha^{-1} in years 2015–2018, respectively. The basic composition of the compost applied included 3 kg Mg^{-1} of available N, 7 kg Mg^{-1} of P_2O_5, and 8 kg Mg^{-1} of K_2O.

Three crops were planted annually: corn, soybean and a small grain (wheat [*Triticum aestivum* L.], spelt [*Triticum spelta* L.], or oat [*Avena sativa* L.]). Corn and soybean were planted every year in early June with a row spacing of 76 cm. Small grains were planted in the fall as a winter cereal, or in the spring. Red clover (*Trifolium pratense*) was frost seeded into winter cereals or drilled after oat harvest. All production practices followed certified organic practices typical of this region, with the exception that there were fewer crops in the rotation than typically found on organic grain farms (Brock, Jackson-Smith, Kumarappan, et al., 2021).

Corn and soybean grain were harvested from the center rows using a small plot combine. Crop yields (2015–2020) were calculated using the grain weight and moisture content from the combine and were adjusted to 155 and 130 g kg^{-1} moisture content for corn and soybean, respectively. In several instances, yields were not obtainable due to either crop failure from weed infestations or poor initial establishment, or because conditions remained too wet for planting.

2.2 | Soil sample collection

Soil samples at both study sites were collected at the end of each growing season from the surface 0–20 cm of all plots. Eight soil cores (2.5-cm diam.) were randomly sampled from each plot and composited into a single sample. Soil samples were passed through an 8-mm sieve, mixed, and air-dried. A subsample was then ground to pass through a 2-mm sieve to determine pH, cation exchange capacity, organic matter and extractable Ca, Mg, K, and sulfur (S) using recommended chemical soil test procedures for the North Central Region (NCERA-13, 2015). Soil pH was determined on a 1:1 soil water slurry using a glass electrode (Peters et al., 2012). Soil organic matter was determined by loss-on-ignition at 360 °C for 2 h (Combs & Nathan, 1998). Extractable Ca, Mg, K, and S were measured using a Mehlich-3 extractant (Mehlich, 1984) and analyzed with an inductively coupled plasma atomic emission spectrophotometer. The Ca/Mg ratios were calculated from the extractable soil cation concentrations.

2.3 | Soil biological health measurements

Permanganate oxidizable carbon was quantified according to Weil et al. (2003), with modifications from Culman et al. (2012). In brief, 2.5 g of air-dried sieved soil was mixed with 20 ml of 0.02 mol L^{-1} $KMnO_4$ in a 50-ml centrifuge tube. The mixture was shaken for 2 min on a horizontal shaker at 240 oscillation min^{-1} and then allowed to settle for 10 min. A 0.5-ml aliquot was collected and transferred into a separate 50-ml centrifuge tube with 49.5 ml of deionized water. The absorbance of the sample was measured at 550 nm on a spectrophotometer.

Mineralizable C (CO_2 respired upon rewetting dried soil) was determined by measuring the CO_2 evolved during a 24-h aerobic incubation (Franzluebbers et al., 2000). A 10-g soil sample was weighed into a 50-ml centrifuge tube and 3 ml of deionized water was added. The tubes were capped and made air-tight with a rubber septum and were incubated at 25 °C for 24 h. After incubation, a 1-ml air sample was collected with a syringe and injected into an LI–820 infrared gas analyzer (LICOR, Biosciences) to determine the CO_2 concentration.

Soil protein was quantified using a neutral sodium citrate buffer (Hurisso, Culman, & Zhao, 2018). Three grams of soil was mixed with 24 ml of 20 mM sodium citrate buffer (pH 7) in a centrifuge tube. The mixture was shaken for 5 min at 180 oscillations min^{-1} and then autoclaved at 121 °C for 30 min. The autoclaved mixture was cooled to room temperature and shaken for 3 min at 180 oscillations min^{-1}. A 1.5-mL sample was transferred to a 2-mL centrifuge tube and centrifuged at $10,000 \times g$ for 3 min. Protein was quantified using colorimet-

ric bicinchoninic-acid assay (Thermo Scientific) in a 96-well spectrophotometric plate reader at 562 nm.

2.4 | Soil physical measurements

Soil aggregate stability was measured by slaking of submerged soil in water using a Yoder apparatus and the method given by Kemper and Rosenau (1986). Five aggregate size classes were measured: >2 mm, 2–0.5 mm, 0.5–0.25 mm, 0.25–0.053 mm, and <0.053 mm. Fifty grams of soil (8-mm sieved and dried) was placed on nested sieves and lowered into deionized water until fully submerged. Samples were immediately subjected to vertical oscillations for 10 min with a stroke of 4 cm at a speed of 30 oscillations min^{-1}. After the 10-min cycle, nested sieves were raised out of the water and allowed to freely drain. Aggregates from each sieve were washed into an aluminum tin, oven-dried, and weighed. Aggregates from each size class were calculated as a percentage of the total sample, with the <0.053-mm sample being determined by difference. The aggregate stability of the soil is given as mean weight diameter (MWD, mm), which is calculated as the sum of products of the mean diameter of each size class and the relative proportion of aggregates in that size class (Kemper & Rosenau, 1986). Two replications were used to measure aggregate stability in each plot and an average was taken for a final plot measurement.

Soil water infiltration at both sites was measured in the fall of 2018 and 2019 using a mini-disk infiltrometer (Meter Group, Inc.) adjusted to a −2 cm suction rate to minimize macropore flow. The mini-disk infiltrometers were placed on a leveled soil surface and the water in the reservoir was allowed to flow through the disk into the dry soil. Infiltration of water was recorded every 3 min at Hirzel and every 2 min at West Badger until there was a constant change in volume for a minimum of three consecutive intervals. The cumulative infiltration was fitted with a square root of time function and the infiltration rate was determined using the method proposed by Zhang (1997). Three replications were used to measure infiltration in each plot and an average was taken for a final plot measurement. The penetration resistance (PR) of the soil was measured in the fall of 2019 using an electronic Spot-On cone penetrometer (Innoquest, Inc.). Thirty penetrometer readings were taken systematically at 0-to-10- and 10-to-20-cm depths in each plot. For each depth, the average of 30 readings was calculated as a final plot measurement.

2.5 | Data analysis

Soil was sampled and analyzed for the first 5 yr (2015–2019) of the study, whereas crop yields were measured for an additional year, for a total of 6 yr (2015–2020). All the data were

TABLE 2 Soil chemical properties (mean ± standard error) at the end of 2019 after epsom and gypsum applications at the two study sites

Site	Treatment	Soil pH	CEC	OM	Ca	Mg	K	S
			cmol$_c$ kg^{-1}	g kg^{-1}	——————————————mg kg^{-1}——————————————			
Hirzel	Control	6.8 ± 0.1	21.0 ± 1.4	29.0 ± 0.2	3617 ± 263	517 ± 41 b	205 ± 10.6	12.3 ± 0.3 c
	Epsom	6.9 ± 0.1	20.9 ± 0.5	29.0 ± 1.5	3429 ± 179	655 ± 36 a	191 ± 1.3	54.0 ± 5.8 b
	Gypsum	7.0 ± 0.2	19.8 ± 0.8	26.8 ± 1.0	3911 ± 340	468 ± 11 b	199 ± 5.4	75.8 ± 5.7 a
West Badger	Control	6.4 ± 0.0	6.5 ± 0.5 b	17.8 ± 0.6	905.3 ± 51 b	215 ± 16 b	203 ± 15	9.1 ± 0.3 c
	Epsom	6.3 ± 0.0	7.3 ± 0.2 ab	18.5 ± 0.9	764.0 ± 44 c	317 ± 22 a	184 ± 13	18.5 ± 1.4 b
	Gypsum	6.4 ± 0.1	7.6 ± 0.4 a	16.8 ± 1.4	1,136 ± 62 a	187 ± 12 b	193 ± 17	28.3 ± 3.0 a

Note. Treatment means in a column followed by different letters are significantly different from each other within a site at $p <.05$.

initially subjected to normal distribution and equality of variance tests using the Shapiro–Wilks test. When the data were not normal, a log transformation of data was performed. Raw or transformed data were subjected to analysis of variance (ANOVA) using the PROC MIXED model in SAS v9.4 to determine the significance ($P <0.05$) of main plot (crop) and subplot (amendments) factors and their respective interactions. Crop and amendment effects were assumed as fixed and block was considered a random effect, with year as a repeated measure for the yield data. If the yield data were significantly different by year and site ($P \leq .05$), ANOVA was run for each year and site separately. For soil nutrient concentrations, if the effect of crop was not significant on tested parameters, means were calculated across the two crops for each subplot treatment. Mean comparisons between treatments were conducted using the adjusted Tukey's test in the LSMEANS routine in SAS. A simple linear regression analysis was performed to test the relationship between Ca/Mg ratios and crop yields using the *lm()* function in R (R Core Team, 2020). All the figures were generated using the *'ggplot2'* package in R.

3 | RESULTS AND DISCUSSION

3.1 | Extractable soil nutrient levels and Ca/Mg ratios

Applications of gypsum and epsom over 5 yr influenced soil Mehlich-3 extractable Ca and Mg levels at both sites (Table 2). Gypsum application increased soil extractable Ca levels by 8 and 26%, at Hirzel and West Badger, respectively, relative to the control. The increases were statistically significant only for West Badger's silt loam soil, which had a lower cation exchange capacity than the clay loam soil at the Hirzel site. Epsom significantly increased extractable Mg levels at both sites relative to the control soils. These results were expected as both gypsum and epsom are readily available sources of Ca and Mg and previous studies have reported similar changes in soil extractable Ca and Mg concentrations after application (Chaganti et al., 2019; Chen & Dick, 2011; Kost et al., 2014;

Mikkelsen, 2010). The decrease in availability of soil Mg with gypsum application and, conversely, the decrease in Ca availability with epsom application demonstrate the antagonistic effect among soil nutrients. However, these reductions did not cause cation levels to drop below their critical levels (Culman et al., 2020), so the risk of base cation nutrient deficiency was highly unlikely.

Application of gypsum and epsom significantly increased Mehlich-3 S levels, a result commonly reported in previous studies (Chaganti et al., 2019; Dash & Ghosh, 2012; Raut et al., 2020; Wang & Yang, 2018; Table 2). As expected, application of either gypsum or epsom (neutral salts) did not affect soil pH. Similarly, gypsum and epsom application did not alter soil K levels (Table 2). Some previous studies have reported that nutrient ion interactions are possible, especially between K and Ca or Mg (Fageria, 2001), and could lead to plant deficiencies. However, we found that application of either gypsum or epsom did not significantly change K levels in plant tissue (data not shown).

Gypsum application increased Ca/Mg ratios and epsom application decreased Ca/Mg ratios, and these differences grew greater over time (Figure 1). Amendment applications showed a more pronounced effect in altering Ca/Mg ratios at the silt loam West Badger site, ranging from 2.5 to 6.1, relative to the clay loam Hirzel site (ranging from 5.3 to 8.4). Changes in Ca/Mg ratios were expected given our large application rates (>10 Mg ha^{-1}).

3.2 | Soil biological health

Gypsum and epsom application had no effect on measured soil biological health properties (Table 3). Across all treatments, mean POXC concentrations were 599 and 402 mg kg^{-1} at Hirzel and West Badger, respectively. Mean mineralizable C concentrations were 68 and 74 mg kg^{-1} and mean protein concentrations were 3.9 and 4.5 g kg^{-1} at Hirzel and West Badger, respectively. We are aware of only one other study to have evaluated the effects of Ca/Mg ratios on these soil biological health indicators of active organic matter.
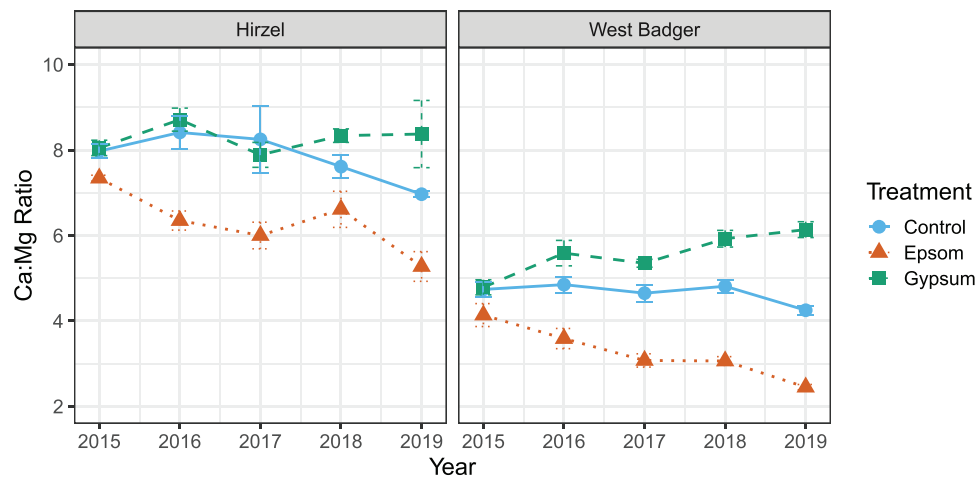
FIGURE 1 Soil Ca/Mg ratios (mean ± standard error) over 5 yr (2015–2019) with application of epsom (red triangles, dotted line) or gypsum (green squares, dashed line) relative to the control (blue circles, solid line) at both the study sites

TABLE 3 Soil biological health indicators (mean ± standard error) at the end of 2019 as influenced by epsom and gypsum application at the two study sites

Site	Treatment	Permanganate oxidizable carbon	Mineralizable C	Soil protein
		—————————mg kg^{-1}—————————		g kg^{-1}
Hirzel	Control	592.5 ± 32	62.2 ± 9.9	3.82 ± 0.4
	Epsom	605.3 ± 31	71.3 ± 4.3	4.07 ± 0.3
	Gypsum	599.8 ± 28	70.4 ± 3.7	3.88 ± 0.2
West Badger	Control	392.3 ± 24	74.8 ± 7.9	4.49 ± 0.3
	Epsom	408.1 ± 9.1	73.3 ± 7.7	4.57 ± 0.3
	Gypsum	406.8 ± 21	73.8 ± 4.9	4.34 ± 0.2

Note. Treatment means in a column not followed by differnt letters are not significantly different from each other within each site at $p < .05$.

Schonbeck (2000) examined BCSR effects across five diverse vegetable farms in Virginia and Tennessee and found no impact on POXC, respiration, microbial biomass, or other biological measurements. Numerous studies have demonstrated that these three indicators are sensitive to recent changes in management (Culman et al., 2012, 2013; Franzluebbers, 2016; Hurisso et al., 2016; Roper et al., 2017; van Es & Karlen, 2019) and more sensitive than total SOM or soil organic carbon across diverse agroecosystems. Practitioners of BCSR often describe improvements in soil biological activity in balanced soils (Brock, Jackson-Smith, Culman, et al., 2021). Our results suggest that, after 5 years, manipulating Ca/Mg ratios had no measurable impact on soil biological health at either site (Table 3).

3.3 | Soil physical properties

Soil aggregate stability (MWD) was not affected by application of gypsum or epsom at both Hirzel and West Badger sites (Table 4). As expected, there were significant differ-

ences between the two sites in terms of soil MWD, with the MWD at Hirzel significantly higher than West Badger. Average MWD across all treatments was 1.43 and 0.89 mm at the Hirzel and West Badger sites, respectively. These results were unexpected as gypsum is known to promote Ca mediated soil aggregate stability (Amézketa, 1999; Rowley et al., 2018). On the other hand, excess Mg in the soil was previously shown to reduce soil aggregation by increasing soil dispersion and therefore negatively affecting soil aggregate stability (Rengasamy et al., 1986; Zhang & Norton, 2002; Zhu et al., 2019). However, it is important to highlight those studies demonstrating soil disaggregation effects of Mg were seen at saturation levels above 75%, which is unrealistic under normal field conditions in this region (Chaganti & Culman, 2017). Nevertheless, such antagonistic effects of Ca and Mg on soil aggregate stability were not observed in this study, as indicated by lack of significant differences between control and epsom or gypsum treatments. These results provide no evidence to support the common belief of soil balancing practitioners that BCSR alters soil aggregation and therefore soil structure.

TABLE 4 Soil aggregate stability by mean weight diameter (MWD) and percent recovery of aggregate size classes (mean ± standard error) at the end of 2019 as influenced by epsom and gypsum applications at the two study sites

Site	Treatment	MWD	>2,000 μm	250-500 μm	53-250 μm	<53 μm
		mm			%	
Hirzel	Control	1.49 ± 0.01	69.5 ± 0.8	23.0 ± 0.2	6.3 ± 0.5	1.2 ± 0.1
	Epsom	1.39 ± 0.06	63.9 ± 3.2	26.7 ± 1.7	7.9 ± 1.2	1.6 ± 0.3
	Gypsum	1.41 ± 0.05	64.8 ± 3.2	26.1 ± 1.9	7.6 ± 1.0	1.5 ± 0.3
West Badger	Control	0.85 ± 0.06	33.9 ± 3.2	34.0 ± 2.5	25.2 ± 1.8	6.9 ± 0.7
	Epsom	0.92 ± 0.03	38.3 ± 2.1	31.3 ± 2.6	24.1 ± 0.9	6.3 ± 0.4
	Gypsum	0.91 ± 0.09	37.5 ± 4.7	30.9 ± 0.7	23.9 ± 3.2	7.7 ± 1.5

Note. Treatment means in a column not followed by different letters are not significantly different from each other within each site at $p < .05$.

TABLE 5 Soil penetration resistance (PR) and soil water infiltration (mean ± standard error) at the end of 2019 as influenced by epsom and gypsum applications at the two study sites

Site	Treatment	PR 0-10 cm	PR 10-20 cm	Infiltration
		kPa		cm hr^{-1}
Hirzel	Control	560 ± 42.8	809 ± 50.7	0.34 ± 0.07
	Epsom	603 ± 33.7	837 ± 30.3	0.42 ± 0.06
	Gypsum	574 ± 27.4	797 ± 25.7	0.35 ± 0.11
West Badger	Control	1506 ± 28.7	1934 ± 51.1	0.15 ± 0.02
	Epsom	1532 ± 74.5	1954 ± 68.7	0.16 ± 0.02
	Gypsum	1728 ± 93.7	2125 ± 68.2	0.17 ± 0.02

Note. Treatment means in a column not followed by different letters are not significantly different from each other within each site at $p < .05$.

Application of epsom or gypsum did not significantly affect soil PR at either of the study sites (Table 5). Average PR was 579 and 814 kPa at 0-to-10- and 10-to-20-cm depths, respectively, across all treatments at the Hirzel site. Similarly, average PR across all treatments was 1,586 and 1,999 kPa at 0–10 and 10–20 cm, respectively, for West Badger. High PR observed at the West Badger site indicates that the soil was compacted (Benevenute et al., 2020) compared with those soils at Hirzel. This can be mostly attributed to the coarse nature of soils (Barbosa et al., 2018; de Lima et al., 2017; de Oliveira et al., 2016) found at West Badger rather than changes in Ca/Mg ratios caused by gypsum or epsom applications.

Water infiltration rates were not significantly affected by gypsum or epsom applications at either site, with average infiltration rates of 0.37 and 0.17 cm h^{-1} at Hirzel and West Badger, respectively (Table 5). Gypsum is a well-known soil amendment for improving water infiltration in soil due to the aggregatory effects of Ca (Bronick & Lal, 2005; Grant et al., 1992). Studies have reported excess Mg in the soil causing soil dispersion and negatively affecting soil aggregation (Keren, 1991; Smith et al., 2015; Zhu et al., 2019). The positive or negative effects associated with Ca and Mg were not observed in this study as substantiated by unchanged soil aggregate stability (Table 4). Our results corroborate those of He et al. (2013), who also reported no effect of altered Ca/Mg ratios on soil dispersion and therefore no effect on soil water infiltration.

3.4 | Crop yields

Application of either gypsum or epsom to alter Ca/Mg ratios did not have any significant effect on either corn or soybean grain yields in any of the years, nor were there any discernible trends found with treatments over 6 yr, indicating application of amendments had no impact on crop productivity (Table 6). Corn and soybean yields ranged between 2.41 and 7.28 Mg ha^{-1} and 1.77 and 3.75 Mg ha^{-1}, respectively, at the Hirzel site across all years, and ranged between 4.18 and 11.2 Mg ha^{-1} and 1.76 and 3.24 Mg ha^{-1}, respectively, across all years at West Badger. This variation in yields across time can be attributed to variability in growing season environmental conditions over the course of this study. Nevertheless, the grain yields of corn and soybean observed in our study are comparable to those reported by some previous studies under organic cropping systems (Chalise et al., 2019; Clark et al., 2017; Kravchenko et al., 2017; Liebman et al., 2018).

There was no significant relationship between crop yields and Ca/Mg ratios over 6 yr of this experiment (Figure 2) for Hirzel and West Badger sites. This indicates that there was

TABLE 6 Corn and soybean grain yields (mean ± standard error) over 6 yr (2015–2020) as influenced by epsom and gypsum applications at the two study sites

Site	Crop	Treatment	2015	2016	2017	2018	2019	2020
					—Mg ha^{-1}—			
Hirzel	Corn	Control	2.86 ± 0.5	5.66 ± 0.4	6.40 ± 0.3	6.19 ± 0.3	–	–
		Epsom	2.66 ± 0.6	5.19 ± 0.1	6.54 ± 0.1	6.65 ± 0.1	–	–
		Gypsum	2.41 ± 0.6	7.28 ± 0.1	6.23 ± 0.3	6.38 ± 0.2	–	–
	Soybean	Control	2.16 ± 0.2	–	1.99 ± 0.1	–	–	3.75 ± 0.4
		Epsom	2.02 ± 0.2	–	2.04 ± 0.01	–	–	3.63 ± 0.4
		Gypsum	1.77 ± 0.7	–	1.93 ± 0.1	–	–	3.58 ± 0.3
West Badger	Corn	Control	4.48 ± 0.7	5.73 ± 0.2	8.05 ± 0.9	10.4 ± 0.6	10.5 ± 0.5	10.50 ± 0.6
		Epsom	4.24 ± 0.9	4.54 ± 0.3	8.03 ± 0.5	10.0 ± 0.3	10.6 ± 0.7	10.88 ± 1.4
		Gypsum	4.18 ± 0.4	4.31 ± 0.4	7.70 ± 0.7	10.3 ± 0.3	10.3 ± 0.5	11.15 ± 0.3
	Soybean	Control	–	2.00 ± 0.3	3.02 ± 0.4	2.87 ± 0.2	2.27 ± 0.5	3.21 ± 0.1
		Epsom	–	1.94 ± 0.2	3.09 ± 0.3	2.74 ± 0.2	2.38 ± 0.3	2.79 ± 0.3
		Gypsum	–	1.76 ± 0.2	3.24 ± 0.2	2.91 ± 0.1	2.28 ± 0.4	3.00 ± 0.3

Note. Treatment means in a column not followed by different letters are not significantly different from each other within each site at $p < .05$.
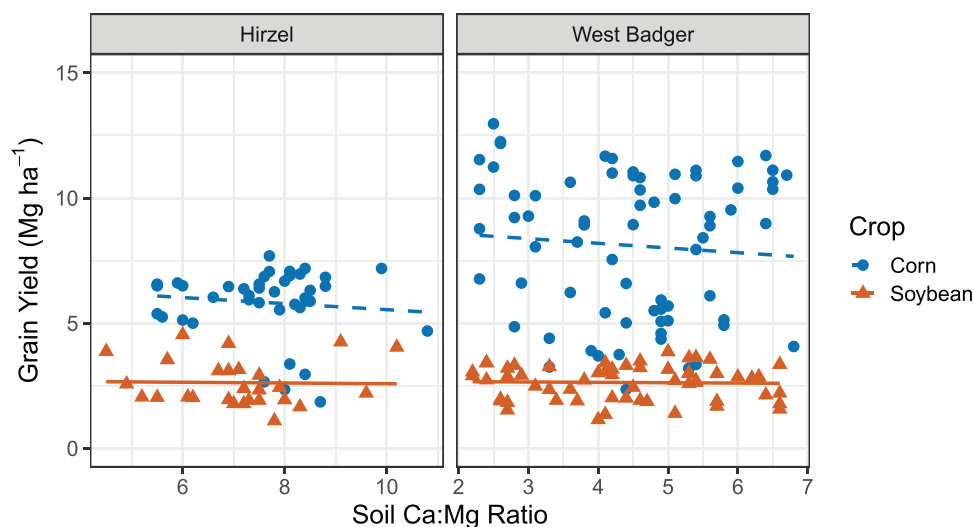
FIGURE 2 Relationship between corn (blue circles) and soybean (red triangles) grain yield and soil Ca/Mg ratios over 6 yr (2015–2020) of the experiment at both the study sites

no ideal base cation ratio where yields of corn and soybean were maximized. Our results match with previous studies conducted decades ago, which also reported no yield response to altered Ca/Mg ratios (Chaganti & Culman, 2017). For example, Schulte and Kelling (1985) conducted a similar experiment in Wisconsin by applying gypsum and epsom to alter soil Ca/Mg ratios and measured corn and alfalfa (*Medicago* spp.) yield response. They concluded that the yields of corn and alfalfa were not influenced by changing Ca/Mg ratios as a result of gypsum and epsom application. Similarly, McLean et al. (1983) tested the yield response of corn and soybean in Ohio. These authors reported that Ca/Mg ratios ranged between 2.30 to 26.8 and that there was no ideal ratio where crop yields were maximized. In the current study, Ca/Mg ratios across 5 yr ranged between 4.5 to 10.8 at Hirzel and 2.2 to 6.8 at West Badger, and yet there was no strong relationship found between crop yields and Ca/Mg ratios. In a more comprehensive analysis, Olson et al. (1982) also concluded that there was no agronomic or economic basis that an ideal Ca/Mg ratio produces higher yields. Our results, therefore, support the conclusions derived from previous studies that crop yields would not be affected by BCSR as long as sufficient levels of nutrients are maintained to meet crop needs.

4 | CONCLUSIONS

Repeated application of gypsum and epsom significantly altered Ca/Mg ratios at both the study sites. Despite these differences, we found no effects of Ca/Mg ratios on grain yields of either corn or soybean in any of the 6 study years. In addition, despite testimonials of altered soil structure with changing Ca/Mg ratios from BCSR practitioners, we did not find any evidence of altered soil structure in this study, as aggregate stability, PR, and water infiltration were not affected by either epsom or gypsum application. Soil biological health was also not impacted by either gypsum or epsom application as there were no significant differences observed within POXC, mineralizable C, and soil protein. We therefore conclude that this study provides no evidence to support an ideal cation saturation ratio where maximum yields are found. Our data corroborate other reports that yields are not related to base cation ratios. This is the first report of BCSR practices in organic field crop systems and the first study to comprehensively evaluate soil biological, chemical, and physical properties. Overall, our results align with the conclusions of previous studies, providing no objective evidence to support the claims of BCSR theory with respect to soil health and crop yields.

AUTHOR CONTRIBUTIONS

Catherine Herms: Conceptualization; Formal analysis; Investigation; Writing-review & editing. Caroline Christine Brock: Conceptualization; Data curation; Writing-original draft; Writing-review & editing. Andrea Leiva Soto: Data curation; Formal analysis; Investigation; Writing-review & editing. Douglas Doohan: Conceptualization; Funding acquisition; Project administration; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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