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Crop Management

Managing soil acidity vs. soil Ca:Mg ratio: What is more important for crop productivity?

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Abstract

Soil balancing (SB), or base cation saturation ratio (BCSR), is a soil management approach that strives to maintain specific soil calcium (Ca) and magnesium (Mg) levels to improve soil health, decrease pest problems, have better crops, and increase crop yield. To achieve ideal levels of Ca to Mg, BCSR practitioners apply gypsum (calcium sulfate) and high-calcium lime (Hi-Cal lime) amendments, with the former increasing Ca base saturation and the later increasing both Ca base saturation and soil pH. We hypothesized that positive benefits ascribed by BCSR practitioners are due to increasing soil pH, rather than increasing Ca levels, both of which occur after lime application. Thus, we conducted successive applications of gypsum or epsom (magnesium sulfate) with and without Hi-Cal or dolomitic lime, to either increase or lower soil Ca:Mg ratio and pH in an Ohio-based experiment over 6 yr and evaluated soil and yield responses in a corn (*Zea mays* L.)–soybean (*Glycine max* L.)–small grain rotation. Repeated applications of gypsum with and without Hi-Cal lime significantly increased soil Ca:Mg ratio and repeated applications of epsom with and without dolomitic lime significantly decreased the soil Ca:Mg ratio. Crop yield was not affected by soil Ca:Mg ratio for any crop in any year. However, over the 6 yr of the study, corn yields were positively related to increases in soil pH. We conclude that balancing soil Ca and Mg levels did not impact corn or soybean yields but managing soil acidity remains a fundamental tool to improve crop yields.

1 | INTRODUCTION

Soil balancing (SB), or the base cation saturation ratio (BCSR) method, is a soil management approach that strives to achieve basic cation saturation ranges of 60 to 75% for calcium (Ca), 10 to 20% for magnesium (Mg), 3 to 5% potassium (K), and 15% for other cations (Chaganti & Culman, 2017). The benefits claimed by BCSR practitioners of increasing soil Ca compared to soil Mg levels are broad, including improvements in soil health, fewer pest problems, better crops, and increases in crops yield (Brock et al., 2021). Despite lack of Land Grant University endorsement for decades (Culman et al., 2021), many conventional farmers (Cantarella et al., 1998; Johnston, 2005; Wood & Litterick, 2017; Zalewska et al., 2018), sports turf industry professionals (Kopittke & Menzies, 2007), and a majority of organic farmers in the U.S. Midwest (Brock

Abbreviations: BCSR, base cation saturation ratio; CEC, cation exchange capacity; Hi-Cal, high-calcium; SB, soil balancing.

TABLE A. Useful conversions

To convert Column 1 to Column 2, multiply by		Column 1 suggested unit	Column 2 SI unit
		Length	
0.304		foot, ft	meter, m
1.609		mile, mi	kilometer, km
2.54		inch	centimeter, cm (10^{-2} m)
		Mass	
0.454		pound, lb	kilogram, kg
907		ton (2000 lb), ton	kilogram, kg
0.907		ton (2000 lb), ton	megagram, Mg (tonne)
		Yield and rate	
62.71		56-lb bushel per acre, bu ac^{-1} (corn)	kilogram per hectare, kg ha^{-1}
67.19		60-lb bushel per acre, bu ac^{-1} (soybean)	kilogram per hectare, kg ha^{-1}
2.24		ton (2000 lb) per acre, t ac^{-1}	megagrams per hectare, Mg ha^{-1}
1.12		pound per acre, lb ac^{-1}	kilogram per hectare, kg ha^{-1}
		Temperature	
5/9 (˚F – 32)		Fahrenheit, ˚F	Celsius, ˚C
		Concentration	
1		parts per million, ppm	milligrams per kilogram, mg kg^{-1}
1		milliequivalents per 100 grams, meq 100 g^{-1}	centimole per kilogram, cmol kg^{-1}
		Plant nutrient conversion	
Oxide		*Elemental*	
0.437	P_2O_5	P	2.29
0.830	K_2O	K	1.20

Core Ideas

- Application of lime to soil raises both pH and calcium saturation levels.
- We tested the relative effects of soil pH vs. Ca:Mg ratio on corn and soybean yield.
- Over 6 yr, corn yields increased with soil pH but not with soil Ca:Mg ratio.
- There was no yield benefit between high-calcium vs. dolomitic limestone.
- Managing soil acidity remains a fundamental tool for crop production.

et al., 2020) use BCSR to interpret soil analyses and guide fertilization programs.

Calcium and Mg are essential nutrients for plant growth (Hirschi, 2004; Shaul, 2002), but their role in soil, particularly their relative influence on soil structure, is not well understood (Chaganti & Culman, 2017; Culman et al., 2021). Calcium plays a role in improving soil aggregation by complexing to organic matter substrates and to the negatively charged surfaces of clay particles (Clough & Skjemstad, 2000; Rowley et al., 2018; Six et al., 2004), playing a putatively important role in soil organic carbon stabilization (Rowley et al., 2018). However, there are conflicting reports on the role that Mg plays in promoting or reducing soil aggregation and water infiltration (Chaganti & Culman, 2017). For example, studies have shown that excessive soil Mg can reduce soil aggregation and infiltration (Keren, 1991; Smith et al., 2014; Zhu et al., 2019) and others have shown no impact (Chaganti et al., 2021; He et al., 2013). The positive impacts of increasing Ca saturation levels claimed by BCSR practitioners is commonly attributed to the idea that high soil Mg levels lead to 'tight' soils and reduced aeration (Brock et al., 2021). However, these claims have yet to be documented robustly in a field setting (Chaganti et al., 2021).

To achieve ideal levels of Ca and Mg, BCSR practitioners typically apply gypsum (calcium sulfate) and high-calcium lime (Hi-Cal lime; Brock et al., 2020). Although there's no universally accepted definition of Hi-Cal lime, it typically refers to lime with higher Ca and lower Mg concentrations than traditional agricultural lime (Brock et al., 2020). Gypsum is a soil amendment that typically has minimal effect on soil pH but does provide a readily available source of Ca and sulfur (S) for plant nutrition (Watts & Dick, 2014). Gypsum is used to remediate sodic soils (Mao et al., 2016; Wamono et al., 2016), promote rainwater infiltration, reduce soil dispersion and crusting (Yu et al., 2003), and ameliorate toxic effects of subsoil acidity (De Castro Pias et al., 2020; Lynch et al., 2012; Zhang & Rengel, 2000). In contrast, limestone amendments are mainly used to correct soil acidity and increase soil pH (Fageria & Baligar, 2008). Soil Ca saturation also increases after lime is applied. It is widely acknowledged that soil acidity can be a major constraint to crop growth, and consequently, to crop yield. Crops in acid soils usually experience aluminum (Al) and manganese (Mn) toxicity, and deficiencies of Mg, Ca, phosphorus (P), and molybdenum (Mo; George et al., 2012; Haynes & Naidu, 1998). Base cation saturation ratio practitioners typically use soil pH to determine whether to apply Hi-Cal lime (low pH soils, ~ <6.0) or gypsum (optimal pH soils, ~6.0–7.0; Culman et al., 2021).

Given the lack of positive effects of BCSR management on crop yields in published studies (Kopittke & Menzies, 2007; Chaganti et al., 2021), we questioned whether the positive benefits attributed to a higher Ca:Mg ratio by BCSR practitioners could be due to increasing soil pH, rather than increasing Ca saturation levels, both of which typically occur after lime application (Culman et al., 2021). Thus, we hypothesized that optimizing soil pH, not Ca:Mg ratio, would increase grain yields, and that optimizing Ca:Mg ratio without managing soil acidity would have little effect on yields. To test this hypothesis, we used successive applications of gypsum or epsom, with and without Hi-Cal or dolomitic lime, to either increase or lower soil Ca:Mg ratio in an Ohio soil planted to a corn (*Zea mays* L.)–soybean (*Glycine max* L.)–cereal grain rotation and measured the effect on soil properties and crop yields.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

The experiment was established in spring 2015 at the West Badger Research Farm of the Ohio Agricultural Research and Development Center (OARDC; 40˚46′54″N, 81˚51′06″W) in Wooster, Ohio. The field was certified organic since 1998 and was planted in wheat (*Triticum aestivum*), alfalfa (*Medicago sativa*; 3 yr), and corn prior to the experiment. Soil is a moderately well-drained silt loam (Canfield: fine-loamy, mixed, active, mesic Aquic Fragiudalfs) with an initial pH of 5.9, organic matter of 1.4%, and a cation exchange capacity (CEC) of 9 meq 100 g^{-1} (Table 1, with sampling procedures described below). Monthly total precipitation and soil temperature at 2-inch depth were retrieved from the OARDC Wooster campus (40˚46′29″N, 81˚55′4″W) weather station within 4.5 mi of the field.

A split-plot randomized complete block design with four replications was used to test the effect of gypsum or epsom application, with or without lime, on crop yield and soil mineral properties. The crop was the main plot and amendments were applied to subplots. Five amendments were applied: (1) gypsum (calcium sulfate, $CaSO_4$); (2) epsom (magnesium sulfate, $MgSO_4$); (3) gypsum+Hi-Cal lime (gypsum + high-calcium limestone, $CaCO_3$); (4) epsom+dolomite (epsom + dolomitic limestone, $CaMg[CO_3]_2$); and (5) an unamended control. The main plots were 100-ft wide and 40-ft long and subplots were 20-ft wide and 40-ft long. The crop rotation included corn, soybean, and small grains, where each crop was present every year. Small grains were spring planted oats (*Avena sativa* L. 'Deon') in 2015, fall-planted rye (*Secale cereale* L.) in 2015, and spring-planted oats from 2017 to 2020. Oats were drilled with red clover (*Trifolium pratense* L.) all years, except for 2015 when a cover crop mix of radish (*Raphanus sativus* L.) and winter pea (*Pisum sativum* L.) was drilled instead. Small grain yield data were collected inconsistently throughout the study and are therefore not reported here (Supplemental Table S1).

TABLE 1 Baseline soil properties (mean ± standard error, SE) at the West Badger farm in 2015. All nutrients were Mehlich-3 extracted

Soil property[a]	Mean ± SE
Soil pH	5.9 ± 0.04
CEC, meq 100 g^{-1}	9.1 ± 0.49
Organic matter, %	1.4 ± 0.04
Calcium, ppm[b]	965 ± 19.6
Magnesium, ppm[b]	213 ± 9.4
Potassium, ppm[b]	99 ± 2.3
Ca saturation, %[c]	41 ± 2.9
Mg saturation, %[c]	18 ± 1.3
K saturation, %[c]	2.5 ± 0.19
Ca:Mg ratio	4.6 ± 0.15

[a]CEC, cation exchange capacity; Ca, calcium; Mg, magnesium; K, potassium.
[b]Recommended Mehlich-3 extractable levels: Ca > 200 ppm; Mg > 50 ppm; K > 120-160 ppm. Source: Culman et al., 2020.
[c]Recommended base saturation (BCSR): Ca: 60–75%; Mg: 10–20%; K: 2–5%.

Amendments were applied in the spring and fall of 2015, and every spring from 2017 to 2020. Cumulatively over 6 yr (2015–2020), gypsum and epsom treatments received 5.5 t ac^{-1} each of calcium sulfate and magnesium sulfate, respectively, gypsum+Hi-Cal lime treatments received 4.4 t ac^{-1} of calcium sulfate and 3.2 t ac^{-1} of Hi-Cal limestone, and epsom+dolomite treatments received 4.2 t ac^{-1} of epsom sulfate and 3.8 t ac^{-1} of dolomitic limestone. In addition to amendments, 300 lb ac^{-1} of sulfate of potash (K_2SO_4) was applied to all plots in 2015, and composted dairy manure was applied to all crop plots at rates of 16.9, 9.8, 3.1, 11.6, and 7.1 t ac^{-1} in Years 2015 to 2018 and 2020, respectively, except for small grain plots in 2018. Compost mineral analysis included an average of 6 lb t^{-1} of available N, 10 lb t^{-1} of P_2O_5, 18 lb t^{-1} of K_2O, 20.6 lb t^{-1} of Ca, and 5.6 lb t^{-1} of Mg on a wet basis. Amendments were incorporated into the soil using a moldboard plow or via chisel tillage to a depth of 8 inch, aligned with our soil sampling depth.

Corn and soybean were planted on 30-inch rows at densities typical for Ohio organic farms (34,000 seeds ac^{-1} and 170,000 seeds ac^{-1}, respectively). Small grains and cover crops were drilled in 7.5-inch rows using farmer-typical seeding rates. Weeds in corn and soybean were controlled by inter-row cultivation each year, plus additional hand-weeding when needed. At maturity, crops were harvested with a small plot combine from the middle four rows. More details about the experimental site and the field management are provided in Chaganti et al. (2021).

2.2 | Soil sampling and mineral analysis

Initial soil properties were measured across the experimental area in spring 2015 before crop establishment and amendment application (Table 1). Twelve soil cores (1-inch diam.) from 0-to-8-inch deep were randomly collected from each crop-replicate combination and composited into a single sample. To measure the response of soil properties to amendments, soil was sampled each fall from every subplot after crops reached physiological maturity, by sampling eight cores (1-inch diam.) from 0-to-8-inch deep and compositing into a single sample. Soil samples were dried at 105 ˚F and ground to pass through a 2-mm sieve for soil mineral properties, including pH, CEC, organic matter, and Mehlich-3 extractable nutrients (Ca, Mg, K, and S) using the recommended soil test procedures for the North Central Region (NCERA-13, 2015).

2.3 | Statistical analysis

Soil mineral properties and crop yield data were analyzed using a mixed linear analysis of variance (ANOVA) model. Analyses were performed across all crops and by crop, using the PROC MIXED procedure (SAS v9.4) with block as a random effect. When the raw data did not meet the assumptions of ANOVA (homogeneity of variances), transformations were performed prior to analysis. The Tukey–Kramer method ($\alpha = .05$) was used to detect significant differences among amendments. Simple linear regression analyses were performed to test the relationship between soil Ca to Mg ratio, and soil pH, with respect to crops yield. Linear regression and corresponding figures were generated with *lm()* function and *'ggplot2'* package in R (R core Team, 2020). Small grain yields were not included in the regression analysis due to the small sample size.

3 | RESULTS AND DISCUSSION

3.1 | Soil mineral properties response to amendments

Application of amendments over 6 yr altered soil CEC; Mehlich-3 extractable Ca, Mg, and S; and cation base saturation (Table 2). Across crops, soil receiving lime (Hi-Cal lime or dolomite) had increased the soil CEC relative to non-limed soils. These results are consistent with a meta-analysis study reporting a 14% increase in the soil CEC in soils that received lime (n = 78, field trials; Li et al., 2019). Calcium levels increased 52% where gypsum+Hi-Cal lime was added compared to unamended soils, and a 33% increase where gypsum was applied alone, but decreased by 16% where epsom was applied alone (Table 2). The application of gypsum and limestone amendments has been shown to increase the soil exchangeable Ca levels (Kost et al., 2014; Li et al., 2019). Magnesium levels doubled when epsom+dolomite lime was added compared to unamended soils, and there was a 66% increase when epsom was applied alone. The application of epsom or dolomite has been shown to increase the soil extractable Mg levels (Li et al., 2019; Wang et al., 2020). All amendments significantly increased soil extractable S (Table 2). Gypsum and epsom typically increase soil extractable S levels when applied (Chaganti et al., 2019; Dick et al., 2008; Fleuridor et al., 2021). Regarding base saturation (BS), gypsum and gypsum+Hi-Cal lime amendments significantly increased Ca BS, whereas epsom and epsom+dolomite amendments significantly decreased Ca BS relative to the non-amended control (Table 2). Similarly, epsom and epsom+dolomite amendments significantly increased the Mg BS of unamended soils from 24 to 35 and 37%, respectively, whereas gypsum+Hi-Cal lime amendment decreased Mg BS to 18% with respect to unamended soils. As for K BS, all soils, including the unamended soils, were over the BSCR recommendations for BS (>5% K), except for soils applied with epsom+dolomite, which were within the BCSR range. After 6 yr of applications, soils amended with either gypsum or gypsum+Hi-Cal lime would be within BCSR ideal ranges for both Ca and Mg saturation (60–75% Ca, 10–20% Mg), whereas the epsom and epsom+dolomite would be considered highly out of balance.

3.2 | Soil Ca:Mg and soil pH response to amendments

Gypsum amendment with and without Hi-Cal lime increased the soil Ca:Mg compared to unamended soils (Figure 1A). Gypsum+Hi-Cal lime amendment effects were detected after the first application ($p < .001$), and effects of gypsum alone after the second application ($p < .001$). Epsom amendments with and without lime decreased the soil Ca:Mg compared to unamended soils (Figure 1A). Epsom amendment effects (epsom+dolomite and epsom) were detected after the first application ($p < .001$) and resulted in soils having about 47% lower Ca:Mg compared to unamended soils.

As expected, soil pH was mainly affected by Hi-Cal lime and dolomite amendments (Figure 1B). After the third year of amendments, limed treatments had higher pH compared to unamended soils and soils applied with gypsum or epsom alone ($p < .001$). Limed treatments continued to increase soil pH in the following years and amendment effects were maintained until the end of the study, with limed soils having an

TABLE 2 Soil chemical properties (mean ± standard error) in the final year of the study (2020). Values within a column followed by different letters indicate statistically significant differences between amendment treatments (α = .05)

Amendment	CEC[a]	Ca	Mg	S	Ca BS	Mg BS	K BS
	meq/100 g	ppm[b]			%[c]		
Control	6.0 ± 0.4 b	887 ± 26 c	192 ± 8 c	12 ± 0.3 b	55.6 ± 2.6 b	23.6 ± 1.6 b	6.8 ± 0.6 a
Gypsum	6.6 ± 0.3 b	1181 ± 29 b	181 ± 8 c	53 ± 14.6 a	68.0 ± 3.6 a	20.4 ± 1.5 bc	6.2 ± 0.5 ab
Gypsum + Hi-Ca Lime	7.7 ± 0.3 a	1352 ± 56 a	186 ± 11 c	36 ± 9.7 a	66.1 ± 0.8 a	17.8 ± 0.9 c	5.1 ± 0.2 bc
Epsom	6.6 ± 0.1 b	746 ± 16 d	319 ± 12 b	43 ± 3.3 a	42.4 ± 1.1 c	35.4 ± 1.0 a	5.4 ± 0.2 bc
Epsom + dolomite	8.2 ± 0.1 a	980 ± 39 c	408 ± 13 a	31 ± 2.8 a	45.1 ± 1.2 c	36.7 ± 0.5 a	4.9 ± 0.1 c

[a]CEC, cation exchange capacity; Ca, calcium; Mg, magnesium; S, sulfur; BS, base saturation; Hi-Cal, high calcium.
[b]Recommended Mehlich-3 extractable levels: Ca > 200 ppm; Mg > 50 ppm. Source: Culman et al., 2020.
[c]Recommended base saturation (BCSR): Ca: 60–75%; Mg: 10–20%; K: 2–5%.

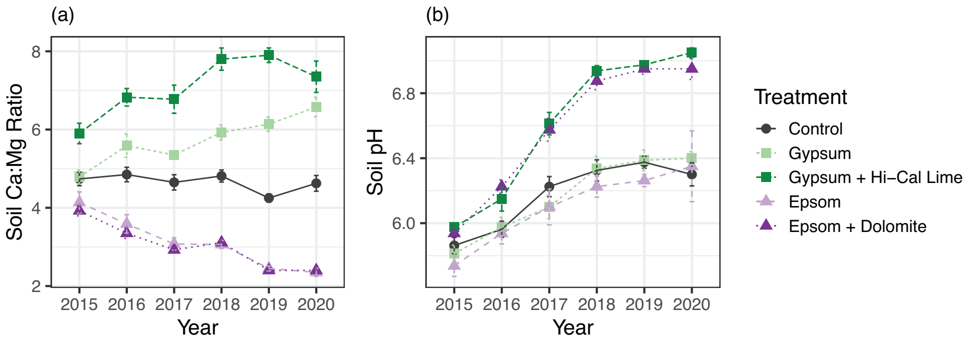

FIGURE 1 Mean soil Ca:Mg ratio (a) and soil pH (b) values over the 6 yr of the study (2015–2020). Error bars represent standard errors of the mean

average pH of 7.0 compared to the average pH of 6.3 in soils from non-limed plots. Studies reported in a meta-analysis showed that 3 yr of liming can significantly affect soil pH, as liming reactions and subsequent changes in soil pH are often not fully realized for several years (Li et al., 2019). Soil pH in all treatments, including the untreated control, increased throughout the study (Figure 1B). After 6 yr, limed soils had an increase in soil pH of 1.0, and non-limed soils had an increase in soil pH of 0.5. The unintended increase in soil pH of non-limed soils was likely from the annual application of composted manure (about 10,500 t ac^{-1} yr^{-1}), as composted manure has been shown to increase soil pH in previously reported studies (Bickelhaupt, 1989; Das et al., 2017; Eghball, 1999; Forge et al., 2016; Pérez-Esteban et al., 2012).

3.3 | Crop yield response to amendments

With the exception of 2016, the application of amendments did not affect corn, soybean (Table 3), or small grain yields (Supplemental Table S1). In 2016, corn yield was highest in the unamended control soils compared to soils receiving amendments (Table 3), which might be due to agricultural practices as corn plots were frequently hand-weeded that year (data not shown). Previous studies have reported no effect on corn yield when applying similar annual rates of gypsum in Ohio soils (Chaganti et al., 2021, 2019; Fleuridor et al., 2021). Average corn yield, across amendments, ranged between 66 and 77 bu ac^{-1} for the first 2 yr and increased from 127 to 175 bu ac^{-1} for the following 4 yr. Soybean yields across amendments averaged 29 bu ac^{-1} the second year and ranged between 33 and 48 bu ac^{-1} through the final year. Previous studies with a similar crop rotation reported yields comparable to the ones observed in this study (Delate & Cambardella, 2004; Porter et al., 2003).

Although crop yield responses to soil amendments were not statistically different in most years, there were some general trends throughout the study. The highest crop yields across all treatments within the first 2 yr were in the untreated soils (Table 3). In the last 4 yr, soils receiving lime (either Hi-Cal or dolomitic) had the highest yields relative to the non-lime amendments (gypsum or epsom) in 4 out of 4 yr for corn and 3 out of 4 yr for soybean (Table 3).

Regression analysis showed no relationship between crop yield and soil Ca:Mg across 11 site-years (Figure 2). These results agree with previous studies on BCSR (Chaganti &

TABLE 3 Corn and soybean yield (mean ± standard error and mean separation) over 6 yr (2015–2020) of amendment applications

Crop	Treatment	2015	2016	2017	2018	2019	2020
		bushels ac^{-1}					
Corn	Control	72 ± 11.9	92 ± 2.6 a	129 ± 14.6	166 ± 9.7	167 ± 7.3	167 ± 9.1
	Gypsum	67 ± 6.4	67 ± 6.9 b	123 ± 11.8	164 ± 5.1	166 ± 7.7	178 ± 4.7
	Gypsum + Hi-Cal[a] lime	56 ± 8.5	83 ± 10.4 b	123 ± 13.6	171 ± 4.1	178 ± 7.6	178 ± 13.7
	Epsom	68 ± 14.1	73 ± 4.0 b	129 ± 8.6	160 ± 4.5	170 ± 11.6	173 ± 22.3
	Epsom + dolomite	66 ± 8.5	70 ± 1.2 b	133 ± 15.6	180 ± 4.3	162 ± 14.3	178 ± 4.2
Soybean	Control	-	30 ± 4.1	45 ± 6.2	30 ± 7.3	34 ± 6.8	48 ± 1.2
	Gypsum	-	26 ± 2.5	49 ± 3.4	37 ± 0.8	34 ± 5.3	45 ± 4.6
	Gypsum + Hi-Cal lime	-	29 ± 5.0	46 ± 8.9	32 ± 4.0	39 ± 2.5	47 ± 1.6
	Epsom	-	29 ± 2.8	46 ± 3.7	35 ± 2.8	36 ± 4.6	42 ± 4.5
	Epsom + dolomite	-	28 ± 0.4	53 ± 3.8	33 ± 2.0	38 ± 6.5	48 ± 1.6

[a]Hi-Cal, high calcium.

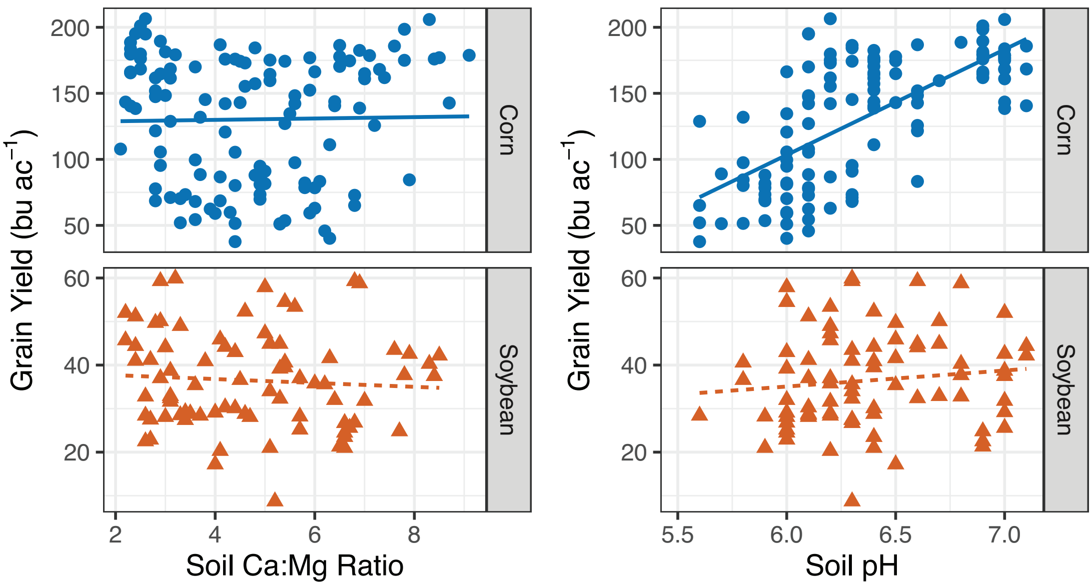

FIGURE 2 Relationship between grain yield and soil Ca:Mg ratio or soil pH. Corn (6 site-years) and soybean (5 site-years) yields are paired with soil data from those plots across the 6 yr (2015–2020)

Culman, 2017; Fox & Piekielek, 1984; Kopittke & Menzies, 2007; Liebhardt, 1981; Simson et al., 1979), which also reported that crop yields were not related to a soil Ca:Mg ratio. However, regression analysis to test the relationship between crop yield and soil pH showed a discernible trend (Figure 2).

Across the six site-years, soil pH showed a positive relationship with corn yields ($y = 80x - 376$; $R^2 = .45$, $p = < .01$, 95% CI [63.8, 96.0]). Soybean yields were less responsive to soil pH across five site-years ($y = 4x + 13$; $R^2 = .01$, $p = .30$, 95% CI [−3.3, 10.6]). These results agree with Pagani & Mallarino (2015), showing that corn yields responded more frequently than soybean yields when applied with Hi-Cal lime. Furthermore, a meta-analysis including 175 peer-reviewed manuscripts reported corn ($n = 71$) as more responsive to liming than soybean ($n = 23$), regardless of the liming source (Li et al., 2019). However, other studies have reported contrasting results of soybean being more responsive to liming (Pierce & Warncke, 2000), both corn and soybean showing inconsistent yield response (Vetsch & Randall, 2006), and both crops showing increases in yield in till (Henning, 2005), and no-till systems (Woodard & Bly, 2010). Different plant species have different CEC (fixed anions) in their root cell walls, and the roots of monocotyledonous species have a lower root CEC compared to the roots

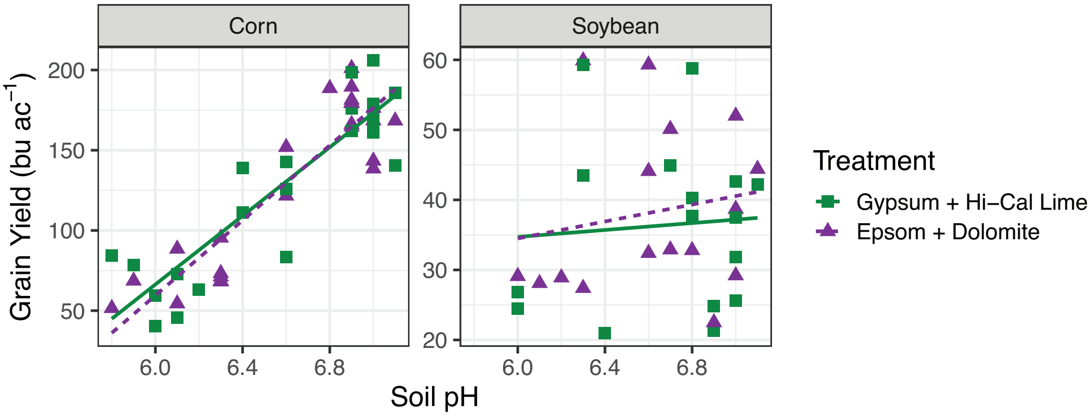

FIGURE 3 Corn and soybean yield and soil pH in response to gypsum+high-calcium (Hi-Cal) lime and epsom+dolomite applications over 6 yr (2015–2020)

of dicots (Keller & Deuel, 1957; White, 2012; White & Broadley, 2003). This results in monocotyledonous species being more susceptible to acid soils compared to dicots. Lower soil pH means more protons (H^+, $Al_3{}^+$, $Mn_2{}^+$) occupy the root exchangeable sites (CEC), which for a species with an already scarce root CEC can result in impeding the exchange of important cations for crop nutrition (Allan & Jarrell, 1989; White, 2012). Even though our study does not show a correlation between soybean yields and soil pH, other studies on Midwestern soils reported decreases in soybean yield when soil pH increased above 7.5 (Kaspar et al., 2004; Rogovska et al., 2007). The negative effect of basic soils on soybean yield can often be attributed to a lower availability of iron (Kaspar et al., 2004; Moraghan & Mascagni Jr., 1991; Zocchi et al., 2007); however, iron deficiencies can also be attributed to biotic factors and agricultural practices, and not only to limited available iron (Hansen et al., 2004). Furthermore, acid soils (pH <6.0) with low Ca concentrations can also negatively affect legume nodulation and nitrogen fixation (Alva et al., 1987; Alves et al., 2021; Ferguson & Gresshoff, 2015; George et al., 2012). These negative effects driven by soil pH were not present in our study. Soybean leaf analysis in the R1 stage never showed iron deficiencies (data not shown), and soils Ca levels were above soil test critical levels when the experiment was initiated (Table 1).

The meta-analysis by Li et al. (2019) reported increases in yields of a broad variety of crop species in response to liming, except for sorghum (*Sorghum bicolor* L.), tuber crops, and tobacco (*Nicotiana tabacum* L.). However, crop yield response to liming can also be attributed to the correction of a mineral deficiency. For example, Li et al. (2019) found that liming with dolomite had a greater effect on crop yields compared to using Hi-Cal lime, yet they concluded that increases in crop yield due to dolomite application mainly reflected the crop's response to Mg inputs, because most field soils were Mg deficient (Li et al., 2019). Our data suggest that there was no difference between the use of limestone or dolomite on crop yields (for corn, gypsum+Hi-Cal lime: R^2 = .81; epsom+dolomite: R^2 = .81; Figure 3). These results agree with other studies reporting that corn and soybean showed no yield differences among liming sources applied (Pagani & Mallarino, 2012; Vetsch & Randall, 2006). The fact that our study shows both limestone and dolomite having the same effect on corn yields is economically relevant for growers. The majority of growers in Ohio purchase dolomitic lime (high-Mg lime; Ohio Department of Agriculture, 2020), and based on a survey conducted in Ohio to organic corn producers, Hi-Cal lime costs roughly twice as much as other sources of lime (Kumarappan et al., 2019). Our data show no yield benefits with using Hi-Cal lime over dolomitic lime, and therefore suggest a lower return on investment with this practice.

4 | CONCLUSIONS

Repeated applications of gypsum with and without Hi-Cal lime increased the soil Ca:Mg ratio and Ca base saturation. In contrast, repeated applications of epsom with and without dolomitic lime decreased soil Ca:Mg ratio and increased Mg base saturation. Even though amendments affected soil Ca:Mg and soil pH for each year of study, amendments rarely affected yields within a given year. However, over the 6 yr of the study, regression analysis revealed corn yields were positively related to increasing soil pH to optimal levels but were not affected by soil Ca:Mg ratio. Soybean yields were not related to either soil Ca:Mg ratio nor soil pH. Finally, we found no yield benefit to using Hi-Cal lime relative to dolomitic limestone for corn and soybean yields. Consistent with previous studies, we conclude that balancing soil Ca and Mg levels did not affect corn or soybean yields but managing soil acidity remains a fundamental tool to improve crop yields and manage soil fertility.

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AUTHOR CONTRIBUTIONS

Andrea Leiva Soto: Data curation; Formal analysis; Visualization; Writing – original draft. **Steve W. Culman**: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Catherine Herms**: Data curation; Formal analysis; Investigation; Writing – review & editing. **Christine Sprunger**: Validation; Writing – review & editing. **Douglas Doohan**: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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