ARTICLE

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Short-term responses of soils and crops to gypsum application on organic farms

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Abstract

Gypsum is a high calcium (Ca) and sulfur (S) containing mineral used to improve soil fertility and physical characteristics in organic cropping systems. However, evidence regarding short-term improvements in soil properties and increased crop yield is lacking. We conducted replicated experiments on 14 different organic dairy farm fields in five Ohio counties in 2017 and 2018. Our analysis evaluated short-term effects of gypsum application on (a) nutrient concentrations in soils and crop tissues, (b) yield of corn (*Zea mays* L.) and forage (alfalfa [*Medicago sativa* L.] or alfalfa–mixed grasses], and (c) and soil health properties. There were no effects on the yield of corn and forage after one or two annual gypsum applications. Still, gypsum consistently increased S concentrations ($P < .1$) in soil and crop tissues as soon as 5 mo after each application. Gypsum had no measured effects on soil mineralizable carbon (C), penetrometer resistance, or unsaturated hydraulic conductivity in the short term. Soil protein, permanganate oxidizable C, and Mehlich-3 magnesium levels were lower after the second application ($P < .1$). Our results indicate a short-term effect on some soil and crop nutrients but no additional benefits to soil health or crop yield in the short term when gypsum was applied to organically managed soils.

1 | INTRODUCTION

The number of certified organic operations in the United States doubled from 2006 to 2016, and organic dairy production is one of the fastest-growing sectors (USDA, 2017). Meeting the complex nutrient management needs of growing organic feed-crops on an annual basis is a particular challenge. A healthy soil, capable of effectively providing nutrients and other ecological services, is considered the foundation for organic production. An approach used to improve soil health by many organic farmers in the Eastern Corn Belt is soil balancing. Soil balancing is centered on the base cation saturation ratio (BCSR) concept and contends there is an ideal soil ratio of approximately 13:2:1 Ca/Mg/K that, when achieved, supports optimum crop growth, quality, and yield (Chaganti & Culman, 2017; Kopittke & Menzies, 2007). Although there has been very little evidence to support this claim since reported by its original proponents in the 1940s, many farmers and crop consultants rely on this method to make fertilization decisions (Chaganti & Culman, 2017).

Abbreviations: BCSR, base cation saturation ratio; CEC, cation exchange capacity; POXC, permanganate oxidizable carbon.

Soil balancing requires repeated and regular applications of Ca-rich minerals, such as gypsum and/or limestone, to achieve the desired balance of cations on the soil exchange sites (Brock et al., 2020; Zwickle, 2011). A balanced soil minimizes potasssium (K) luxury uptake and reduces phosphorus (P) deficiency while optimizing crop growth (Kopittke & Menzies, 2007). However, proponents of soil balancing report a long-term approach, and it may take several years before demonstrable benefits are realized (McKibben, 2012). Although gypsum has been described as a soluble source of Ca and S (Chen & Dick, 2011), Farina and Channon (1988) suggested that measurable yield effects of gypsum may require the passage of at least 4 yr to be detected. However, many organic farmers find these findings contradictory to their beliefs and experiences, claiming an effect in the same growing season or soon after gypsum application (Brock et al., 2020). The application of gypsum to soils is known to provide physical and chemical benefits. Norton and Rhoton (2007) proposed that gypsum improves soil tilth, and similar claims regarding positive effects on soil tilth have been extensively echoed by farmers who practice soil balancing (Brock et al., 2020). Confirmation of beneficial effects on soil structure (Tirado-Corbalá et al., 2019), water infiltration (Jayawardane & Blackwell, 1986), drainage (Tirado-Corbalá et al., 2013), bulk density (Buckley & Wolkowski, 2014), and penetrometer resistance (Ellington, 1986) have all contributed to the greater interest and use of gypsum among farmers (Watts & Dick, 2014; Zoca & Penn, 2017).

Soil and crop responses to gypsum are affected by multiple factors, including inherent edaphic characteristics, previous agricultural practices, and crop species and cultivars (Shainberg et al.,). Therefore, the context of gypsum use is an important consideration because observed responses are often site specific. For example, Caires et al. (2011) found higher corn yield and high levels of Ca and S in amended oxisols 8 yr after gypsum application. Studies conducted in known sodic or highly weathered soils have often resulted in yield responses following improvements of subsoil acidity or reduced Al toxicity soon after gypsum application (Toma et al., 1999; Zoca & Penn, 2017). In contrast, many other studies, including Chaganti et al. (2019), DeSutter et al. (2014), Kost et al. (2014), and Presley et al. (2018), found minimal effects on crop yield in experiments conducted on temperate arable soils in North America. Most of the published results concerning gypsum use on organic farms are from experiments conducted for 5 yr or fewer and often show inconclusive or contradictory results. As an outcome of this schism in the existing literature, articulating a clear understanding of the short-term effects of gypsum on non-sodic soils is challenging.

Gypsum application is a common practice on organic Ohio farms, with over 55% of organic corn farmers routinely applying gypsum (Brock et al., 2020). However, its effect on crop yields and soil properties remains unsubstantiated. Although

Core Ideas

- One or 2 yr of gypsum application did not affect corn and mixed hay forage yields.
- Gypsum consistently increased S concentrations in soil and crop tissue.
- Two consecutive annual applications of gypsum resulted in a decrease in soil Mg.
- Gypsum did not improve soil health properties.

some practitioners claimed to see benefits in less than 2 yr, little scientific evidence supports their claim. In an extensive survey of organic corn farmers in the Eastern Corn Belt ($n = 859$), those practicing soil balancing (soil balancers) reported spending an average additional US$200 ha^{-1} on inputs and reported higher yields compared with non-soil balancers. However, no significance was detected in self-reported economic efficiency compared with non-soil balancers (S. Kumarappan, unpublished data, 2020). Because gypsum is widely used on organic farms, questions have been raised about how beneficial gypsum applications may be in the short term for the soil and for crops. To address this knowledge gap, we conducted replicated experiments on 14 organic farmer fields, tracking the effects of gypsum application over 1 or 2 yr on crops and soil. Individual short-term studies, analyzed separately using ANOVA, can lack statistical power to synthesize the short-term effect of gypsum among the studies. Because of this, we chose a meta-analysis approach to enable more powerful inferences from individual experiments conducted at multiple sites (Madden & Paul, 2011). A meta-analysis quantitatively synthesizes the results of these studies and generates estimates of the size of the weighted average effect of a treatment (or treatments) relative to untreated control (Borenstein et al., 2009). This approach was previously used by Kost et al. (2018) to evaluate the effects of a one-time application of flue gas desulfurization and mined gypsum sources, with data collected over 2 to 3 yr from 10 sites in several states. Here we followed a similar statistical approach. The specific objectives of this study were to determine if beneficial effects of gypsum were detectable on (a) soils and crop tissues, (b) yields of corn and forage, and (c) soil health properties after 1 or 2 yr of application in organic farms.

2 | MATERIALS AND METHODS

2.1 | Study locations, design, and treatments

This research was conducted at 14 different fields across seven farms in the Ohio counties of Holmes (40°56′ N, 81°93 ′W),

Wayne (40°83′ N, 81°89′ W), Hardin (40°66′ N, 83°66′ W), and Logan (40°39′ N, 83°77′ W) and at the Ohio State University Waterman Farm in Franklin County (39°58′ N, 83°00′ W) (Table 1). All fields were certified organic, except for the one at Waterman Farm. Thirteen fields were chosen in 2017, with 11 of those fields used again in 2018. One field was added in 2018, for a total of 25 experiments (field-years) over the two growing seasons. Crops varied across fields and years and included grain corn (*Zea mays* L.), silage corn, forage, and oat (*Avena sativa* L.) (Table 1). Although farm management practices differed between farms and fields, our cooperators shared practices recently reported by Brock et al. (2018). All farmers used organic corn varieties mainly from Great-Harvest, MastersChoice, and Blue River seed companies. Corn was seeded between 70,000 and 82,000 seeds ha^{-1} at 76-cm row spacing, except at Fields 1 and 2, where the cooperator used 91.4-cm row spacing. Corn planting is typically preceded by a moldboard plow. Fertilization is done using either chicken litter (5,000 kg ha^{-1}) or semi-liquid cow manure (120,000–125,000 L ha^{-1}). Forage crops were predominantly alfalfa (*Medicago sativa* L.) and seeded at rates of 13–22 kg ha^{-1}. In mixed fields (Fields 1, 6, 7, and 9), the lower rate was used with an additional seeding of 2 kg ha^{-1} of red clover (*Trifolium pratense* L.) and 3–4 kg ha^{-1} of rye (*Lolium perenne* L.) and/or orchard grass (*Dactylis glomerata* L.). Forage fields received additional manure or foliar application of fish products containing N–P–K early in the spring and/or after forage cuttings.

A randomized complete block design with four replications was implemented at each field, with a block orientation perpendicular to the slope of the field where applicable. Individual blocks measured approximately 74 m^2 and were divided into two plots of 37 m^2. In one plot mined gypsum was applied by hand at 2.24 Mg ha^{-1}; the other plot served as a control and did not receive gypsum. The gypsum application rate was based on typical farmer application rates in Ohio (Brock et al., 2020).

The first application of 2.24 Mg ha^{-1} gypsum was done at the beginning of the 2017 growing season on the 13 unique fields across the state (Table 1). In spring 2018, 11 of those fields used in 2017 received a second application 2.24 Mg ha^{-1} gypsum, and one additional field established in 2018 received a single application. For annual crops, gypsum was typically applied after planting (within 1 wk after emergence) and was not incorporated except through cultivation practices for weed control in corn. For forage crops, gypsum was applied in early spring and not incorporated.

2.2 | Crop data

When corn reached the R1 growth stage (silking), the leaf associated with the primary ear was collected from 10 plants randomly selected within the two middle rows of each plot. Leaves were dried at 35 °C, ground, and analyzed by Spectrum Analytic, Inc., for nutrient concentrations via inductively coupled plasma atomic emission spectroscopy and N concentrations via direct combustion. Grain corn yields were estimated from 3 m of the two center rows of each plot. Corn ears from each plot were placed in cloth bags and dried at 35 °C. The grain was shelled from the cob, dried at 35 °C, and weighed. Final harvest yields were adjusted to 15.5% moisture and extrapolated from weight per plot to weight per hectare. Stalks and leaves (stover) were dried separately at 35 °C, and nutrient concentrations were determined as described above. Crop data were not collected from sites seeded to oat (one site in 2017 and two sites in 2018; Table 1).

Silage corn plots were harvested approximately 45 d after silking. Eight plants were selected at random from the middle two rows of each plot and cut at ground level. Harvested plants were dried at 35 °C and weighed to determine dry biomass. Then whole plants were chipped and subsampled, and nutrient concentration was determined as described above.

Forage yield was estimated from plants cut approximately 8 cm above the ground between the bud and full flower growth stages (for alfalfa). Samples were taken from 1-m^2 quadrats placed at random in the central area of each plot. Subsequent cuttings were collected approximately 28 and 65 d after the first cutting, for a total of three harvest samples from most sites. Forage samples were dried at 35 °C, weighed to determine dry biomass, and analyzed for nutrient content as described above. Forage yields in each plot were calculated by averaging the weights of all cuttings sampled over the season.

2.3 | Soil data

In the spring of each year, prior to the first gypsum application at each field, soil samples were collected to estimate baseline organic matter content, pH, nutrients levels, and cation exchange capacity (CEC) calculated by base summation of Ca, Mg, and K. Ten cores (each 2-cm diameter by 20-cm deep) of soil were collected from randomly selected points in each block prior to splitting the blocks for gypsum treatment. The soil samples were composited by block, air-dried, and ground to <2 mm. A subsample was mailed to Spectrum Analytics, Inc., to determine soil texture, pH, CEC, organic matter, and Mehlich-3 extractable nutrients using procedures recommended for the North Central Region (NCERA-13, 2015). Mehlich-3 is the new default soil extractant for evaluating fertilizer needs (Culman et al., 2020).

In the fall of both years, soil was sampled from individual plots (10 cores per plot) and analyzed for soil nutrients, as outlined above, and soil biologically active organic matter was determined, as outlined below. Permanganate oxidizable carbon (POXC) was measured based on the methods of Weil

TABLE 1 County location, crop rotation, and baseline soil properties for each field site prior to gypsum application

Field no.	County	Crop 2017	Crop 2018	OM[a]	pH[b]	CEC[c] (cmol_c kg⁻¹)	Mehlich-3 concentrations[d] Ca (mg kg⁻¹)	Mg	K	P	S	Ca/Mg
1	Wayne	silage corn	forage[e]	2.2	7.0	10	1,650	264	253	139	14	6.3
2	Wayne	grain corn	silage corn	2.0	6.6	9	1,305	266	145	83	15	4.9
3	Holmes	oats	grain corn	1.7	6.6	8	1,380	179	179	13	10	7.7
4	Holmes	forage	forage	1.0	6.3	6	1,130	137	137	39	12	8.2
5	Holmes	grain corn	oats	1.4	7.7	16	3,960	169	169	100	28	23.5
6	Wayne	forage	forage	1.4	6.8	8	1,360	188	188	14	8	7.2
7	Wayne	grain corn	forage	1.8	7.4	9	1,970	241	241	27	14	8.2
8	Logan	silage corn	oats	1.0	6.3	8	1,090	223	223	32	13	4.9
9	Logan	forage	grain corn	1.3	6.3	9	1,280	310	310	15	9	4.2
10	Logan	grain corn	none	1.2	6.4	7	1,355	216	216	45	9	6.4
11	Hardin	forage	forage	2.1	7.5	15	2,995	468	468	12	11	6.4
12	Hardin	forage	none	2.3	7.2	13	2,566	385	385	270	15	6.7
13[f]	Hardin	none	forage	3.2	7.2	14	2,894	295	295	35	14	9.7
14	Franklin	grain corn	grain corn	1.8	6.9	13	1,943	355	355	239	12	5.5

[a]Organic matter.

[b]Recommended pH for corn is 6.5 and for alfalfa is 6.8.

[c]Cation exchange capacity, estimated by summation of cations.

[d]Critical level of soil nutrients: Ca, <200 mg kg⁻¹; P, 15–25 mg kg⁻¹; K, 100–125 mg kg⁻¹; Mg, <50 mg kg⁻¹.

[e]Forage was between 90 and 95% alfalfa at Fields 4, 11, 12, and 13 and 5–10% mixed grasses (3–4 kg of orchard grass and 2 kg of red clover added to Field 9); 8 kg ha⁻¹ of red clover was added to Fields 6 and 7; Field 1 was seeded with rye grass and white clover.

[f]Field 13 was added in 2018.

et al. (2003) adapted by Culman et al. (2012). In brief, 20 ml of 0.02 mol L^{-1} KMnO$_4$ were added to 50-ml tubes containing 2.5 g air-dried soil. The tubes were shaken for 2 min at 240 oscillations min^{-1} and allowed to settle for 10 min. After settling, 0.5 ml of the supernatant was diluted with 49.5 ml of deionized water, and sample absorbance was read at 550 nm on a spectrophotometer (Epoch, Biotek/Agilent).

Mineralizable C was estimated based on the methods of Franzluebbers et al. (2000). Briefly, 10 g of air-dried soil were measured into 50-ml polypropylene screw-top centrifuge tubes. Soils were then rewetted with deionized water to 50% water-filled pore space, which was previously determined gravimetrically. The tubes were tightly capped and kept in the dark at 25 °C for 24 h, after which time CO$_2$ concentrations were determined with an infrared gas analyzer.

Soil protein was determined following the protocol described in Hurisso et al. (2018). In brief, 24 ml of 0.02 M sodium citrate was added to 3 g of air-dried soil. After shaking for 5 min at 180 oscillations min^{-1}, samples were autoclaved at 121 °C (15 psi) for 30 min. Soil particles were resuspended by shaking for 3 min at 180 oscillations min^{-1}, and then 1.75 ml of the sample slurry was removed and centrifuged (10,000 × g for 3 min). Next, 10 μl of the sample supernatant was combined with 200 μl of bicinchoninic acid working reagent (Pierce, Thermo Scientific) and incubated on a block heater at 60 °C for 60 min. The absorbance in the sample was determined at 562 nm using a spectrophotometer.

The effect of gypsum on soil structure was assessed infield by measuring resistance to penetration and unsaturated hydraulic conductivity. Penetration resistance was measured using a handheld soil compaction probe (DICKEY-john). Sample points were randomly located throughout each plot, and the average of 12 readings from the top 20 cm (i.e., the soil surface layer) in each plot was recorded. Unsaturated hydraulic conductivity (i.e., infiltration) was recorded at five sites in fall 2018 using a mini-disk infiltrometer (METER Group, Inc.). Unsaturated hydraulic conductivity was recorded at intervals of 60–120 s at three randomly located points in each plot. A minimum of 10 readings were recorded depending on soil texture, and infiltration rates were calculated with the supplied METER Excel template.

2.4 | Statistical analysis

Random-effects meta-analytical models were fitted to the data from 2017 and 2018 to estimate the overall mean effect of gypsum on several measured responses, excepting yield. For each response variable, an ANOVA on an individual site-year basis was conducted using PROC GLIMMIX of SAS v.9.4 (SAS Institute Inc.) to obtain estimates of least squares means and standard errors for the two treatments (gypsum and the control) and residual variances for each experiment (field-year).

The resulting data matrix of means and variances was used for the meta-analysis. For each response variable, a weight was estimated as an inverse function of the variance. All models were fitted using PROC MIXED of SAS v.9.4 (SAS Institute Inc.), with restricted maximum likelihood used as the parameter estimation method (REML; Madden & Paul, 2011). Weights were used in the *weight* statement in PROC MIXED. *Estimate* statements in PROC MIXED were then used to estimate the difference (D, the effect size) in the means between the gypsum and control treatments for each response variable. As described by Madden and Paul (2011), D summarizes the overall (population average) treatment effect on a variable, with a positive effect size indicating an increase due to the treatment (gypsum) and a negative effect size implying a decrease. Standard errors of the effect sizes were estimated and used to calculate upper and lower limits of the 95% confidence intervals around the overall mean effect sizes for each response. A p value <.1 was used to assign statistical significance.

The analysis described above did not account for the effects of crops (grain corn, silage corn, or forage) or gypsum application frequency (one or two gypsum applications) on the overall effect. Therefore, the analyses were repeated using crop and gypsum application as categorical moderator variables and fixed effects. Separate analyses were conducted for each response × moderator variable combination, with separate effect size and corresponding 95% confidence interval estimated for each level of each moderator variable.

A different approach was taken to analyze the effect of gypsum on yield to account for variation among crops (grain corn, silage corn, or forage). Data for each crop type were pooled across site-years, and separate multicenter (multi-location) analyses were performed, with treatment as a fixed effect and site-year (experiment) and block nested within site-year as random effects. All analyses were performed in PROC MIXED, with *lsmeans* statements with the *pdiff* and *cl* options used to estimate the difference in mean yield between gypsum and the control and the 95% confidence interval around the estimated difference.

3 | RESULTS AND DISCUSSION

3.1 | Site descriptions

Baseline soil nutrient analysis indicated that all of the soils met most fertility guidelines for corn and forages. Soil pH ranged from slightly acidic (6.3) to slightly alkaline (7.7), and CEC ranged from 6 to 16 cmol$_c$ kg^{-1} soil (Table 1). Calcium, Mg, and K exceeded critical soil levels required for corn and forage production (Culman, et al., 2020). Soil Ca/Mg ratios differed among sites (range, 4.2–23.5). Mehlich-3 extractable S ranged from 8 to 28 mg kg^{-1}.

TABLE 2 Effect of gypsum application on yields of grain corn, silage corn and forage as estimated by effect sizes (D), standard errors (SE), ranges, and p values for each crop

Crop	D[a]	SE[b]	Range[c]	p value
			———Mg ha^{-1}———	
Grain corn	−0.45	1.15	−2.78 to 1.89	.7002
Silage corn	−0.08	0.79	−1.81 to 1.65	.9216
Forage (Cutting 1)	−0.12	0.15	−0.42 to 0.18	.4299
Forage (Cutting 2)	0.34	0.19	−0.05 to 0.74	.0839
Forage (Cutting 3)	−0.02	0.06	−0.14 to 0.11	.8011
Total forage	0.26	0.30	−0.4 to 0.87	.3938

[a]Estimate of effect size as test weight difference for gypsum treatment relative to untreated control.

[b]Standard error of the estimate.

[c]Values are the span from the lower to the higher limits at the 95% confidence interval around the estimated effect means.

3.2 | Crop yield and plant nutrient responses

Gypsum did not affect the yield of grain corn, silage corn, or forage, except for second-cut forage (Table 2; effect estimate $P < .10$). Corn yields ranged between 6.15 and 19.3 Mg ha^{-1} for grain and between 22.0 and 25.2 Mg ha^{-1} for silage (Supplemental Table S1). Forage yields ranged between 0.45 and 10.15 Mg ha^{-1} (Supplemental Table S2). The larger effect estimated in the second forage cutting ($P = .0839$; Table 2) was mainly due to a large difference in Field 4 in 2017, where the yield was 7.50 Mg ha^{-1} in the control, compared with 10.2 Mg ha^{-1} in the gypsum plot (Supplemental Table S2). Overall, these results corroborate several previous reports from experiments in which there was no effect of gypsum on crop yield (DeSutter et al., 2014; Kost et al., 2014; Leiva-Soto, 2018). Ample cow manure was applied on each farm for fertilization, and most of the participating farmers also applied purchased S-containing fertilizer products to their fields. Dick et al. (2015) and Eriksen (2009) mentioned that yield responses to additional S rarely occur in agricultural systems where manure is commonly applied. However, soil balancers promote the use of gypsum for the additional presumed benefits of better tilth and soil health.

Application of gypsum resulted in increased crop tissue N following the first, but not the second, application (Table 3). Mean N values ranged from 1.98 to 4.38% in the control and from 1.88 to 4.28% in crops grown in gypsum-amended plots (Supplemental Table S3). There were no effects on K, Ca, or Mg for either application (Table 3). Sulfur levels in corn ear-leaves and alfalfa/grass forage were within ranges recommended as adequate for crop production by Culman et al. (2020) and were generally higher in plots amended with gypsum (Supplemental Table S3). Similar to our results, Chaganti et al. (2019) and Kost et al. (2018) reported increased S concentrations in tissues but no consistent yield responses. In contrast, Steinke et al. (2015) and Caires et al. (2016) reported increased crop yield concurrent with increases in S and N in crop foliage following gypsum application.

The level of P in plant tissues decreased slightly ($P < .1$) in gypsum-treated plots after the first application but then increased slightly ($P < .1$) after the second application (Table 3). The reduction in tissue P after the first application is likely due to the effect of the Ca in gypsum forming calcium phosphate complexes and making P less available to crops. However, after the second gypsum application we did see a trend of higher P in crop tissues. Recent work in Ohio has shown that gypsum can reduce P loss, making P more available for plant use (King et al., 2016). Although these benefits of gypsum on P, N, and S in crop tissue are small in magnitude, they are valuable to farmers, especially dairy producers for whom animal nutrition is the incentive behind their cropping systems.

3.3 | Soil nutrient responses

Gypsum application resulted in higher levels of Ca ($P < .05$) and S ($P < .05$) in the soil surface (top 20 cm) (Table 3). Mehlich-3 extractable Ca ranged from 1,126 to 4,828 mg kg^{-1}, and Mehilch-3 S ranged from 16 to 70.5 mg kg^{-1} 5 mo after a single gypsum application of 2.24 Mg ha^{-1} (Supplemental Table S4), attesting to the characteristic of gypsum to readily supply both nutrients in available and soluble forms. The second application of gypsum in 2018 further amplified the effect estimates for both nutrients (Table 3).

Soil Mg levels were low compared with the control after 5 mo after the second gypsum application ($P < .05$) (Table 3; Supplemental Table S5) and consistent with the antagonistic effects between Ca and Mg previously reported by Kost et al. (2014) following gypsum use. Calcium is often preferred over Mg at the soil exchange sites due to the stoichiometric nature of the CEC reaction (Chaganti & Culman, 2017). The feature characteristic of gypsum replacing Mg with Ca on soil exchange sites may lead to increased soil flocculation and improved soil physical characteristics (Kopittke & Menzies, 2007), but in some soils, this may also lead to disproportionate levels of Ca and Mg that could adversely affect yield (Leiva-Soto, 2018; Syed & Summer, 1991). Such an effect would be especially important to monitor under low-CEC, light-textured sandy soils (Alva et al., 1998). At our study sites, soil Mg levels remained above 50 mg kg^{-1}, the critical level below which crop yields may be affected adversely (Culman et al., 2020)

3.4 | Soil health indicator responses

We were unable to measure the effect of gypsum on soil health variables 5 mo after the first gypsum application (Table 3). However, following the second application, soil

TABLE 3 Effect of one or two annual gypsum applications on plant tissue (leaf) and soil nutrients, and soil biological and structural parameters, as indicated by effect sizes (D), standard errors (SE), range, and p values

Response variable	Units	First application				Second application			
		D[a]	SE[b]	Range[c]	p value	D	SE	Range	p value
Plant Tissue_Nutrients									
N	%	0.08	0.05	−0.01 to 0.18	.087	0.03	0.06	−0.10 to 0.15	.653
P		−0.02	0.01	−0.04 to 0.00	.056	0.02	0.01	0.00 to 0.04	.093
K		0.00	0.02	−0.04 to 0.04	.98	−0.04	0.05	−0.14 to 0.05	.376
Ca		−0.01	0.02	−0.05 to 0.03	.659	0.03	0.06	−0.09 to 0.15	.622
Mg		0.00	0.02	−0.03 to 0.04	.787	0.00	0.01	−0.02 to 0.03	.949
S		0.35	0.02	0.30 to 0.39	<.001	0.07	0.02	0.03 to 0.12	<.001
Soil_Nutrients (Mehlich-3)									
P	mg kg^{-1}	0.17	0.57	−0.94 to 1.28	.767	1.1	1.08	−1.01 to 3.22	.306
Ca		64.4	24.31	16.66 to 112.05	.008	80.2	33.2	15.06 to 145	.016
S		20.8	3.60	13.76 to 27.89	<.001	22.9	7.34	8.49 to 37.3	.002
K		0.98	2.77	−4.46 to 6.41	.724	0.32	2.46	−4.50 to 5.13	.898
Mg		−0.28	4.23	−8.57 to 8.02	.948	−8.38	2.97	−14.21 to 2.60	.0049
Soil_Biological									
POXC	mg kg^{-1}	−12.4	9.07	−30.15 to 5.44	.173	−26.8	16.3	−58.83 to 5.26	.101
Mineralizable C		−0.79	1.02	−2.79 to 1.21	.437	1.58	1.96	−2.26 to 5.42	.419
Soil protein	g kg^{-1}	0.07	0.07	−0.05 to 0.20	.252	−0.27	0.15	−0.56 to 0.02	.069
Soil_Structural									
Penetration resistance MPa		−0.17	0.11	−0.39 to 0.06	.142	−0.04	0.06	−0.15 to 0.07	.477
Hydraulic conductivity	mm h^{-1}	ND[d]	ND	ND	ND	4.88	3.79	−2.56 to 12.3	0.198

[a]Estimate of effect size as the difference of gypsum treatment relative to untreated control.
[b]Standard error of the estimates.
[c]Values are the span from the lower to the higher limits at the 95% confidence interval around the effect means.
[d]Not determined in 2017.

TABLE 4 Effect of gypsum application on soil chemical properties of Mehlich-3 extractable Ca and S as influenced by crops

Effect	D[a]	SE[b]	Range[c]	p value
Mehlich-3 Ca, mg kg^{-1}				
Treatment (Trt)	73.4	20.8	32.6 to 114	.0004
Trt × grain corn	102	26.2	50.5 to 153	.0001
Trt × silage corn	59.5	61.6	−61.4 to 180	.334
Trt × forage	29.6	33.7	−36.5 to 95.7	.38
Mehlich-3 S, mg kg^{-1}				
Trt	20.7	3.03	14.76 to 26.64	<.0001
Trt × grain corn	17.5	4.16	9.34 to 25.67	<.0001
Trt × silage corn	33.0	6.38	20.45 to 45.49	<.0001
Trt × forage	16.6	3.53	9.63 to 23.47	<.0001

[a]Estimate of effect size as test weight difference for gypsum treatment relative to untreated control.

[b]Standard error of the estimate.

[c]Values are the span from the lower to the higher limits at the 95% confidence interval around the estimated effect means.

protein ($P < .1$) was lower in gypsum-treated plots, ranging from 4.3 to 7.2 g kg^{-1} and from 4.1 to 6.6 g kg^{-1} in control and gypsum-treated plots, respectively (Supplemental Table S6). There was also a trend for lower POXC ($P = 0.1013$) in treated plots (Table 3). Individual trial means for POXC ranged from 418 mg C kg^{-1} to 742 mg kg^{-1} for the control and from 359 to 669 mg C kg^{-1} in gypsum-treated plots (Supplemental Table S6). We did not observe an effect of gypsum on mineralizable C. In contrast, Carter (1986) measured a reduction in mineralizable C after 4 wk and then again after 7 yr following a single application of gypsum. Other studies have reported contrasting results on the impacts of gypsum on soil health. Inagaki et al. (2016) found that the addition of gypsum increased pools of labile soil organic C, along with increased arylsulfatase activity, a measure of microbial activity. However, Presley et al. (2018) failed to detect an effect of gypsum on soil microbial biomass and/or microbial community composition after 3 yr.

3.5　|　Soil structural responses

Five of the sites sampled in 2018 for penetration resistance had average resistance values in both gypsum-treated and untreated plots that exceeded 2 MPa (Supplemental Table S7), levels considered to be restrictive of root penetration (Reynolds et al., 2002). Gypsum application reduce penetration resistance (Table 3). Similarly, unsaturated hydraulic conductivity measurements (see Supplemental Table S7 for mean site values) taken in 2018 were not affected by gypsum application (Table 3). The failure to demonstrate consistent effects on soil tilth in the short term is typical of gypsum studies in non-sodic soils (Buckley & Wolkowski, 2014; Zoca & Penn, 2017; Presley et al., 2018).

3.6　|　Interaction of crop and gypsum effects on soil nutrients and soil biology

3.6.1　|　Influence of crop on soil nutrients

Gypsum is a soluble mineral that provides dissolved Ca ions that can gradually move downward through the soil profile, potentially increasing stratification in Ca concentration. This may affect Ca uptake differently for different crops. In our experiments, gypsum had a greater effect on soil Ca in the corn cropping system than in forages (Table 4). Effect sizes in grain corn and silage corn were 102 and 59.5 mg kg^{-1}, respectively, compared with 29.6 mg kg^{-1} in forage. However, the effect was statistically significant only for grain corn ($P < .10$). In contrast, crop type did not influence the concentration of S in the soil following gypsum application (Table 4), likely because sulfate is more soluble and more easily transported through the soil profile than Ca (Dick et al., 2015).

3.6.2　|　Influence of application frequency on soil nutrients and health

Soil Mg, POXC, and soil protein responded only to the second gypsum application (Table 5), supporting the conclusion that gypsum can take multiple years or repeated applications to impart measurable effects on soil properties. Although the observed reduction in Mg concentration in gypsum-treated soils was consistent with our predictions, the reductions in POXC and soil protein, which are the two soil health indicators associated with organic matter stabilization (Culman et al., 2012; Hurisso et al., 2016), were not expected. Both POXC and soil protein are related to soil aggregation and

TABLE 5 Effect of gypsum application on Mehlich-3 extractable soil Mg, permanganate oxidizable C (POXC), and soil protein as influenced by the frequency of application

Effect	D[a]	SE[b]	Range[c]	*p* value
Mehlich-3 Mg, mg kg^{-1}				
Treatment (Trt)	−4.56	2.77	−10.0 to 0.88	.1003
Trt × Application-1	1.39	3.41	−5.29 to 8.08	.6823
Trt × Application-2	−8.36	3.18	2.12 to 14.6	.0087
Soil POXC, mg kg^{-1}				
Trt	−15.30	8.2	−31.38 to 0.78	.0623
Trt × Application-1	10.02	10.68	−10.94 to 30.98	.3485
Trt × Application-2	−24.56	14.3	−3.5 to 52.63	.0862
Soil protein, g kg^{-1}				
Trt	−0.04	0.07	−0.18 to 0.09	.5525
Trt × Application-1	0.07	0.07	−0.2 to 0.05	0.2524
Trt × Application-2	−0.27	0.11	−0.49 to 0.05	0.0161

[a]Estimate of effect size as difference for gypsum treatment relative to untreated control.

[b]Standard error of the estimate.

[c]Values are the span from the lower to the higher limits at the 95% confidence interval around the estimated effect means.

the mineral-associated organic matter fraction (Hurisso et al., 2018; Jensen et al., 2019) and are viewed to be sensitive indicators of organic matter change. As discussed earlier, because Ca is often preferred over Mg at the soil exchange sites (Chaganti & Culman, 2017) and an increase in soil exchangeable Ca is often related to increased organic matter (Rowley et al., 2018), we predicted that POXC and soil protein would increase. Despite these possible pathways for building organic matter, our data suggest these processes are not detectable within the first 2 yr of gypsum application.

4 | CONCLUSIONS

This is the first meta-analysis investigating the short-term effects of gypsum on a large series of replicated field experiments in different locations and environmental conditions in the Eastern Corn Belt. Ultimately, our study strengthened the idea that gypsum can be used to address immediate crop nutrients needs (N, S, and potentially P) and failed to demonstrate a consistent impact on crop yield in the short term. Our data suggest that 2 yr are insufficient to see detectable effects of gypsum application on soil physical properties and soil health. However, the observed negative effects of gypsum on soil POXC and soil protein identified in this study merit future investigation.

Most organic farming practices are driven by empirical knowledge, farmers' observations and beliefs (Brock, Jackson-Smith & Kumarappan, 2018). Despite testimonies among some practitioners of soil balancing that gypsum application can immediately benefit soil health and tilth, we found no evidence to support this claim. For any possible perceived improvements in soil health and structure will likely require longer period and repeated gypsum applications. This may affect decisions organic farmers make regarding how much to invest in gypsum and when these investments will yield beneficial returns.

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REFERENCES

Alva, A. K., Prakash, O., & Paramasivam, S. (1998). Flue-gas desulfurization gypsum effects on leaching of magnesium and potassium from a candler fine sand. *Communications in Soil Science and Plant Analysis*, *29*(3–4), 459–466. https://doi.org/10.1080/00103629809369958

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2009). *Introduction to meta-analysis*. John Wiley and Sons. https://doi.org/10.1002/9780470743386

Buckley, M. E., & Wolkowski, R. P. (2014). In-season effect of flue gas desulfurization gypsum on soil physical properties. *Journal of Environment Quality*, *43*(1), 322. https://doi.org/10.2134/jeq2012.0354

Brock, C., Jackson-Smith, D., & Kumarappan, S. (2018). *A profile of organic corn production in the midwest and northeast*. https://offer.osu.edu/offer.osu.edu/research/orgcorn

Brock, C., Jackson-Smith, D., Kumarappan, S., & Brown, C. (2020). *Farmer and practitioner conceptions and experiences with soil balancing*. The Ohio State University.

Caires, E. F., Joris, H. A. W., & Churka, S. (2011). Long-term effects of lime and gypsum additions on no-till corn and soybean yield and soil chemical properties in southern Brazil: Liming and gypsum in no-till farming. *Soil Use and Management*, *27*(1), 45–53. https://doi.org/10.1111/j.1475-2743.2010.00310.x

Caires, E. F., Zardo Filho, R., Barth, G., & Joris, H. A. W. (2016). Optimizing nitrogen use efficiency for no-till corn production by improving root growth and capturing NO_3-N in subsoil. *Pedosphere*, *26*(4), 474–485. https://doi.org/10.1016/S1002-0160(15)60058-3

Carter, M. R. (1986). Microbial biomass and mineralizable nitrogen in solonetzic soils: Influence of gypsum and lime amendments. *Soil Biology and Biochemistry*, *18*(5), 531–537. https://doi.org/10.1016/0038-0717(86)90011-8

Chaganti, V. N., & Culman, S. W. (2017). Historical perspective of soil balancing theory and identifying knowledge gaps: A review. *Crop, Forage & Turfgrass Management*, *3*(1). https://doi.org/10.2134/cftm2016.10.0072

Chaganti, V. N., Culman, S. W., Dick, W. A., & Kost, D. (2019). Effects of gypsum application rate and frequency on corn response to nitrogen. *Agronomy Journal*, *111*(3), 1109. https://doi.org/10.2134/agronj2018.10.0683

Chen, L., & Dick, W. A. (2011). *Gypsum as an agricultural amendment: General use guidelines*. The Ohio State University Extension.

Culman, S. W., Snapp, S. S., Freeman, M. A., Schipanski, M. E., Beniston, J., Lal, R., Drinkwater, L. E., Franzluebbers, A. J., Glover, J. D., Grandy, A. S., Lee, J., Six, J., Maul, J. E., Mirksy, S. B., Spargo, J. T., & Wander, M. M. (2012). Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. *Soil Science Society of America Journal*, *76*(2), 494–504. https://doi.org/10.2136/sssaj2011.0286

Culman, S. W., Fulford, A. M., Camberato, J., & Stienke, K. (2020). *Tri-state fertilizer recommendations for Corn, soybeans, wheat and alfalfa*. Ohio State University Extension Publishing.

Desutter, T. M., Cihacek, L. J., & Rahman, S. (2014). Application of flue gas desulfurization gypsum and its impact on wheat grain and soil chemistry. *Journal of Environment Quality*, *43*(1), 303. https://doi.org/10.2134/jeq2012.0084

Dick, W. A., Kost, D., & Chen, L. (2015). Availability of sulfur to crops from soil and other sources. In J. Jez (Ed.), *Sulfur: A missing link between soils, crops, and nutrition* (Vol. 50; pp. 59–82). ASA, CSSA, and SSSA. https://doi.org/10.2134/agronmonogr50.c5

Ellington, A. (1986). Effects of deep ripping, direct drilling, gypsum and lime on soils, wheat growth and yield. *Soil and Tillage Research*, *8*, 29–49. https://doi.org/10.1016/0167-1987(86)90321-1

Eriksen, J. (2009). Soil sulfur cycling in temperate agricultural systems. *Advances in Agronomy*, *102*, 55–89. https://doi.org/10.1016/S0065-2113(09)01002-5

Farina, M. P. W., & Channon, P. (1988). Acid-subsoil amelioration: II. Gypsum effects on growth and subsoil chemical properties. *Soil Science Society of America Journal*, *52*(1), 175–180. https://doi.org/10.2136/sssaj1988.03615995005200010031x

Franzluebbers, A. J., Haney, R. L., Honeycutt, C. W., Schomberg, H. H., & Hons, F. M. (2000). Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. *Soil Science Society of America Journal*, *64*(2), 613–623. https://doi.org/10.2136/sssaj2000.642613x

Hurisso, T. T., Culman, S. W., Horwath, W. R., Wade, J., Cass, D., Beniston, J. W., Bowles, T. M., Grandy, A. S., Franzluebbers, A. J., Schipanski, M. E., Lucas, S. T., & Ugarte, C. M. (2016). Comparison of permanganate-oxidizable carbon and mineralizable carbon for assessment of organic matter stabilization and mineralization. *Soil Science Society of America Journal*, *80*(5), 1352. https://doi.org/10.2136/sssaj2016.04.0106

Hurisso, T. T., Moebius-Clune, D. J., Culman, S. W., Moebius-Clune, B. N., Thies, J. E., & van Es, H. M. (2018). Soil protein as a rapid soil health indicator of potentially available organic nitrogen. *Agricultural & Environmental Letters*, *3*(1), 180006. https://doi.org/10.2134/ael2018.02.0006

Inagaki, T. M., De Moraes Sá, J. C., Caires, E. F., & Gonçalves, D. R. P. (2016). Lime and gypsum application increase biological activity, carbon pools, and agronomic productivity in highly weathered soil. *Agriculture, Ecosystems and Environment*, *231*, 156–165. https://doi.org/10.1016/j.agee.2016.06.034

Jayawardane, N. S., & Blackwell, J. (1986). Effects of gypsum-slotting on infiltration rates and moisture storage in a swelling clay soil. *Soil Use and Management*, *2*(3), 114–118. https://doi.org/10.1111/j.1475-2743.1986.tb00693.x

Jensen, J. L., Schjønning, P., Watts, C. W., Christensen, B. T., Peltre, C., & Munkholm, L. J. (2019). Relating soil C and organic matter fractions to soil structural stability. *Geoderma*, *337*, 834–843. https://doi.org/10.1016/j.geoderma.2018.10.034

King, K. W., Williams, M. R., Dick, W. A., & Labarge, G. A. (2016). Decreasing phosphorus loss in tile-drained landscapes using flue gas desulfurization gypsum. *Journal of Environmental Quality*, *45*(5), 1722–1730. https://doi.org/10.2134/jeq2016.04.0132

Kopittke, P. M., & Menzies, N. W. (2007). A review of the use of the basic cation saturation ratio and the "ideal" soil. *Soil Science Society of America Journal*, *71*(2), 259–265. https://doi.org/10.2136/sssaj2006.0186

Kost, D., Chen, L., Guo, X., Tian, Y., Ladwig, K., & Dick, W. A. (2014). Effects of flue gas desulfurization and mined gypsums on soil properties and on hay and corn growth in eastern Ohio. *Journal of Environmental Quality*, *43*(1), 312–321. https://doi.org/10.2134/jeq2012.0157

Kost, D., Ladwig, K. J., Chen, L., Desutter, T. M., Espinoza, L., Norton, L. D., Smeal, D., Torbert, H. A., Watts, D. B., Wolkowski, R. P., & Dick, W. A. (2018). Meta-analysis of gypsum effects on crop yields and chemistry of soils, plant tissues, and vadose water at various research sites in the USA. *Journal of Environment Quality*, *47*(5), 1284. https://doi.org/10.2134/jeq2018.04.0163

Leiva Soto, A. S. (2018). *Title effects of soil balancing treatments on soils, vegetable crops and weeds in organically managed farms* [Master's thesis, Ohio State University]. https://etd.ohiolink.edu/apexprod/rws_olink/r/1501/10?clear=10&p10_accession_num=osu151514193894181

Madden, L. V., & Paul, P. A. (2011). Meta-Analysis for evidence synthesis in plant pathology: An overview. *Phytopathology*, *101*(1), 16–30. https://doi.org/10.1094/PHYTO-03-10-0069

McKibben, W. (2012). *The art of balancing soil nutrients: A practical guide to interpreting soil tests*. Acres, U.S.A.

NCERA-13. (2015). *Recommended chemical soil test for the North Central Region. North Central Region Research Publication. No. 221. Missouri Agricultural Experiment Station SB 1001*. University of Missouri. https://hdl.handle.net/10355/58260

Norton, L. D., & Rhoton, F. (2007). *FGD gypsum influences on soil surface sealing, crusting, infiltration, and runoff*. Paper presented at the Workshop on Agricultural and Industrial Uses of FGD Gypsum, Atlanta, GA. http://www.soilsolutions.net/wp-content/uploads/2015/02/Gypsum-Influences-on-Soil-Surface-Sealing-Crusting-Infiltration-and-Runoff-Norton-Rhoton.pdf

Presley, D., He, Y., & Tomlinson, P. (2018). Soil health and yields on non-sodic soils amended with flue gas desulfurization gypsum. *Crop, Forage & Turfgrass Management*, *4*(1), 180001. https://doi.org/10.2134/cftm2018.01.0001

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., & Lu, X. (2002). Indicators of good soil physical quality: Density and storage parameters. *Geoderma*, *110*(1–2), 131–146. https://doi.org/10.1016/S0016-7061(02)00228-8

Rowley, M. C., Grand, S., & Verrecchia, É. P. (2018). Calcium-mediated stabilisation of soil organic carbon. *Biogeochemistry*, *137*(1–2), 27–49. https://doi.org/10.1007/s10533-017-0410-1

Syed-Omar, S. R., & Sumner, M. E. (1991). Effect of gypsum on soil potassium and magnesium status and growth of alfalfa. *Communications in Soil Science and Plant Analysis*, *22*(19–20), 2017–2028. https://doi.org/10.1080/00103629109368554

Steinke, K., Rutan, J., & Thurgood, L. (2015). Corn response to nitrogen at multiple sulfur rates. *Agronomy Journal*, *107*(4), 1347–1354. https://doi.org/10.2134/agronj14.0424

Tirado-Corbalá, R., Slater, B. K., Dick, W. A., Bigham, J., & Muñoz-Muñoz, M. (2019). Gypsum amendment effects on micromorphology and aggregation in no-till Mollisols and Alfisols from western Ohio, USA. *Geoderma Regional*, *16*, e00217. https://doi.org/10.1016/j.geodrs.2019.e00217

Tirado-Corbalá, R., Slater, B. K., Dick, W. A., Bigham, J., & Mccoy, E. (2013). Hydrologic properties and leachate nutrient responses of soil columns collected from gypsum-treated fields. *Soil and Tillage Research*, *134*, 232–240. https://doi.org/10.1016/j.still.2013.08.007

Toma, M., Sumner, M. E., Weeks, G., & Saigusa, M. (1999). Long-term effects of gypsum on crop yield and subsoil chemical properties. *Soil Science Society of America Journal*, *63*(4), 891. https://doi.org/10.2136/sssaj1999.634891x

USDA. (2017). 2016 count of certified organic operations shows continued growth in U.S. market. https://www.ams.usda.gov/press-release/2016-count-certified-organic-operations-shows-continued-growth-us-market

Watts, D. B., & Dick, W. A. (2014). Sustainable uses of FGD gypsum in agricultural systems: Introduction. *Journal of Environment Quality*, *43*(1), 246–252. https://doi.org/10.2134/jeq2013.09.0357

Weil, R. R., Islam, K. R., Stine, M. A., Gruver, J. B., & Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, *18*(1), 3–17. https://doi.org/10.1079/AJAA200228

Zoca, S. M., & Penn, C. (2017). An important tool with no instruction manual. *Advances in Agronomy*, *144*, 1–44. https://doi.org/10.1016/bs.agron.2017.03.001

Zwickle, S. L. (2011). *Weeds and organic weed management: Investigating farmer decisions with a mental model's approach*. Ohio State University.

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