Sustainable Uses of FGD Gypsum in Agricultural Systems: Introduction

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Interest in using gypsum as a management tool to improve crop yields and soil and water quality has recently increased. Abundant supply and availability of flue gas desulfurization (FGD) gypsum, a by-product of scrubbing sulfur from combustion gases at coal-fired power plants, in major agricultural producing regions within the last two decades has attributed to this interest. Currently, published data on the long-term sustainability of FGD gypsum use in agricultural systems is limited. This has led to organization of the American Society of Agronomy’s Community “By-product Gypsum Uses in Agriculture” and a special collection of nine technical research articles on various issues related to FGD gypsum uses in agricultural systems. A brief review of FGD gypsum, rationale for the special collection, overviews of articles, knowledge gaps, and future research directions are presented in this introductory paper.

The nine articles are focused in three general areas: (i) mercury and other trace element impacts, (ii) water quality impacts, and (iii) agronomic responses and soil physical changes. While this is not an exhaustive review of the topic, results indicate that FGD gypsum use in sustainable agricultural production systems is promising. The environmental impacts of FGD gypsum are mostly positive, with only a few negative results observed, even when applied at rates representing cumulative 80-year applications. Thus, FGD gypsum, if properly managed, seems to represent an important potential input into agricultural systems.

Increasing the productivity of agricultural soils is important to sustainably supply food, feed, fuel, and fiber for a growing human population. The demand for increased productivity has resulted in the search for alternative management practices to increase crop yields. Recent industry claims that flue gas desulfurization (FGD) gypsum, used as a soil amendment, will increase soil and crop productivity and sustainability have sparked interest among producers, stakeholders, and researchers to evaluate the potential benefits. This special collection of papers includes a range of articles addressing gypsum’s sustainable use in agricultural systems.

The use of gypsum, a soft calcium sulfate dihydrate mineral (CaSO₄·2H₂O), in agriculture and for other land applications was reviewed by Chen and Dick (2011). Gypsum’s benefits as a plant nutrient source and soil conditioner for agricultural production have been known since colonial times, dating back to the late 18th century (Crocker, 1922). The use of gypsum, however, was largely discontinued in the United States due to extraction and transportation cost from mines, primarily in Nova Scotia (Canada), to markets in the American colonies. Consequently, gypsum use as an agricultural amendment was largely forgotten except for peanut (Arachis hypogaea L.) production—where calcium (Ca) is essential for maintaining yields—and a few specialty crops (Chen and Dick, 2011).

Gypsum is an excellent soil amendment, supplying readily available Ca and SO₄ ions for plant nutrition (Table 1; Shainberg et al., 1989; Chen et al., 2005; Chen et al., 2008). It is considered moderately soluble in soil, thereby slowly releasing sulfur (S) for multiple years. Agronomists are predicting that crop deficiencies will become common due to a shift from S-containing fertilizers (e.g., superphosphate), pesticides, and decreasing atmospheric deposition within the last 30 yr, resulting in reduced soil S supplies. Moreover, crop yields are also increasing, resulting in greater S removal. For instance, corn (Zea mays L.) removes approximately 18 kg ha⁻¹ for grain to 40 kg ha⁻¹ for silage, assuming a 12 Mg ha⁻¹ grain harvest (Murrell, 2008). The combination of reduced inputs and increased S removal from

Abbreviations: FGD, flue gas desulfurization.
soil has sparked interest in evaluating responses of crops to gypsum additions.

Calcium is also a nutrient important for good root growth, especially where the subsoil has suboptimum pH values (Toma et al., 1999). Compared with limestone, gypsum is 200 times more soluble when applied to soil at a neutral pH (EPRI, 2006). Gypsum’s solubility allows movement of Ca and S through the soil profile into rooting zones (Chen and Dick, 2011). In addition to supplying Ca and S for plant nutrition, gypsum can be used as a soil conditioner to improve physical and chemical properties by promoting better aggregation, increasing water infiltration and movement through the profile, reclaiming sodic soils, mitigating subsoil acidity and Al toxicity (Shainberg et al., 1989), and reducing soluble phosphorus (P) loss from agricultural fields (Table 2; Watts and Torbert 2009).

Gypsum presently marketed for agricultural use is derived from two main sources: mined gypsum from natural geologic deposits and synthetic gypsum produced as a by-product of industrial processes. Several synthetic gypsum sources are currently available, including phosphogypsum from wet-acid production of phosphoric acid from rock phosphate, recycled casting gypsum from various manufacturing processes, recycled wall board gypsum, and FGD gypsum from power plants. In 2012, synthetic gypsum accounted for approximately 54% of the total domestic gypsum supply. Flue gas desulfurization gypsum was by far the largest synthetic source produced and marketed, with more than 23 million Mg generated in 2012 (USGS, 2013). There are strong indications that FGD gypsum production will continue to increase in coming years as utilities comply with air quality regulations, making it a very attractive fertilizer (Ca and S) and conditioner for both sodic and acid soils. Indeed, agronomic gypsum use has increased (American Coal Ash Association, 2013) as a result of its greater availability and distribution of sources in major agricultural producing regions within the United States.

Flue gas desulfurization gypsum is a by-product of S removal from fuel combustion gases, primarily at coal-fired power plants. The removal is generally achieved through a wet scrubbing process that injects a lime or limestone reagent into the flue gases path to capture sulfur dioxide as calcium sulfite, which is then converted to gypsum (calcium sulfate dihydrate) through forced air oxidation (Kairies et al., 2006). The final product is often >95% pure, with the consistency of lime. It generally has finer, more uniform particles than commercially mined gypsum sources (Srivastava and Jozewicz, 2001; Chen et al., 2008). Flue gas desulfurization gypsum may contain higher metals than some mined sources, but concentrations are lower than background levels stipulated for soils (EPRI, 2011; Smith et al., 2013). The metals in FGD gypsum, and their potential release to plants and water through land application, have been extensively studied and are not considered to pose any serious environmental concerns (Chen et al., 2014; Briggs et al., 2014). However, research related to environmental concerns continues.

Flue gas desulfurization gypsum supplies are expected to increase in the United States as electric utilities add more scrubbers to comply with environmental regulations. In 2011, approximately 47% of the FGD gypsum produced was beneficially used (American Coal Ash Association, 2013). Of this amount, about 544,000 Mg was used in agriculture (Table 3). Agricultural and other land application uses of FGD gypsum result in lower operation and maintenance costs for utilities, especially costs related to land-filling. In addition, local beneficial use of FGD gypsum lessens the demand for virgin gypsum production and land degradation associated with mining, reduces manufacturing energy expenditures, and avoids long distance transportation costs. Thus, beneficial use of FGD gypsum can provide benefits to agriculture, utilities, and the environment.

### Objective and Rationale for the Special Collection

Traditionally, mined gypsum has been widely used as a calcium additive for peanut production in the southeastern United States and as a soil conditioner in arid/semiarid regions of the Northern Great Plains and other parts of the world. Recently, interest in FGD gypsum use as a viable low-cost alternative to mined gypsum for improved agricultural production has become a hot topic of discussion among producers. Past research involving gypsum for agricultural and land application uses has primarily

### Table 1. Comparison of chemical properties of gypsum (CaSO₄·2H₂O) and calcite (CaCO₃), two sources of calcium available for land application uses.

<table>
<thead>
<tr>
<th>Property</th>
<th>CaSO₄·2H₂O</th>
<th>CaCO₃ (calcite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight (g/mole)</td>
<td>172.2</td>
<td>100.1</td>
</tr>
<tr>
<td>Ca content (%)</td>
<td>23.3</td>
<td>40.0</td>
</tr>
<tr>
<td>S content (%)</td>
<td>18.6</td>
<td>0</td>
</tr>
<tr>
<td>Standard solubility constant</td>
<td>3.14 × 10⁻³</td>
<td>3.36 × 10⁻³</td>
</tr>
</tbody>
</table>

### Table 2. Summary of potential gyspums uses for agricultural and other land application uses.

<table>
<thead>
<tr>
<th>Potential use</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Source of Ca to improve soil structure, water infiltration, soil aeration and reduce soil erosion</td>
<td></td>
</tr>
<tr>
<td>5. Improved rooting of many crops</td>
<td></td>
</tr>
<tr>
<td>6. Control of soluble phosphorus runoff from fields</td>
<td></td>
</tr>
</tbody>
</table>
been conducted using mined gypsum. Given FGD gypsum’s availability and its smaller and more uniform particle size than commercially mined gypsum, this synthetic source may provide greater soil improvement benefits. Further, gypsum’s impact on agricultural production and the environment will vary depending on crop, region, climatic conditions, and soil properties. Therefore, research is needed to assess plant production and environmental effects of FGD gypsum. Additional published data on FGD gypsum uses in agriculture would be beneficial to the scientific community and resource managers, enabling them to make prescriptions that implement gypsum into soil management practices.

**Paper Summaries Included in the Special Collection**

The nine papers on sustainable agricultural gypsum use are summarized in Table 4. They are grouped into three main topics: (i) mercury (Hg) and other trace elements, (ii) water quality, and (iii) agronomic responses and soil physical properties. Overlaps among these topics make soil and water quality an important theme in many of these papers. This special section in the *Journal of Environmental Quality* is by no means an exhaustive review of sustainable gypsum uses, and readers are encouraged to look up the review articles and references cited in this collection.

**Mercury and Other Trace Elements**

A major concern with FGD gypsum application to soil for agricultural or other uses is that it often contains higher Hg concentrations than does mined gypsum. Concentrations of Hg in FGD gypsum range from 10 to 1400 μg kg\(^{-1}\) (Chen et al., 2014; EPRI, 2011). Briggs et al. (2014) investigated Hg release to air from FGD gypsum-treated soils. In this study, three FGD gypsum sources were mixed with three soils (0–15 cm soil layer) at 4.5, 45, and 170 Mg ha\(^{-1}\), representing approximately 1, 10, and 80 yr of application. Gypsum desulfurization was also surface applied at a rate of 4.9 Mg ha\(^{-1}\), simulating no-till management. Mercury concentrations of the three FGD gypsum sources ranged from 79 to 391 μg kg\(^{-1}\), compared with 1.0 and 2.0 μg kg\(^{-1}\) in mined gypsum, used as a comparison treatment. Total Hg concentrations in soils, with FGD gypsum, ranged from 21 to 48 μg kg\(^{-1}\), which is below that considered representative of natural background soils (100 μg kg\(^{-1}\)). The percentage of total Hg released from treated soil into the atmosphere was comparable to untreated soil. This was much less (<1% of total Hg applied) than the amount of Hg emitted when FGD gypsum was placed alone in a Petri dish (26–68% of total Hg). This suggests that Hg interactions in soil can significantly reduce emissions to the atmosphere. Total Hg and methyl Hg in irrigation drainage water and total Hg concentrations measured from plants were also similar for treated and untreated soils.

A study by Chen et al. (2014) investigated Hg as well as 14 other trace elements in soil and earthworms, used as bioindicators of element availability, when FGD gypsum was land applied. This study was conducted at four field sites across the United States (Wisconsin, Ohio, Indiana, and Alabama). Gypsum application rates ranged from 2.2 Mg ha\(^{-1}\) in Indiana to 20 Mg ha\(^{-1}\) in Ohio and Alabama. These rates are 2 to 10 times higher than typically recommended. The length of time from gypsum application to sampling was 4 mo in Wisconsin, 5 and 18 mo in Ohio, 6 mo in Indiana, and 11 mo in Alabama. Among the elements examined, Hg was slightly increased in soils and earthworms from FGD gypsum treatments compared with both the control

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**Table 3.** FGD gypsum production, total use, and agricultural use in the United States for the last 10 yr for which data are available, 2003–2012.

<table>
<thead>
<tr>
<th>Year</th>
<th>FGD gypsum production</th>
<th>Total use</th>
<th>Agricultural use</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>10,300,000</td>
<td>7,000,000</td>
<td>70,000</td>
</tr>
<tr>
<td>2004</td>
<td>10,800,000</td>
<td>7,500,000</td>
<td>30,000</td>
</tr>
<tr>
<td>2005</td>
<td>10,900,000</td>
<td>8,200,000</td>
<td>119,000</td>
</tr>
<tr>
<td>2006</td>
<td>11,000,000</td>
<td>8,900,000</td>
<td>328,000</td>
</tr>
<tr>
<td>2007</td>
<td>11,100,000</td>
<td>8,400,000</td>
<td>115,000</td>
</tr>
<tr>
<td>2008</td>
<td>11,200,000</td>
<td>8,000,000</td>
<td>341,000</td>
</tr>
<tr>
<td>2009</td>
<td>11,300,000</td>
<td>8,500,000</td>
<td>344,000</td>
</tr>
<tr>
<td>2010</td>
<td>11,400,000</td>
<td>8,900,000</td>
<td>328,000</td>
</tr>
<tr>
<td>2011</td>
<td>11,500,000</td>
<td>9,500,000</td>
<td>302,000</td>
</tr>
</tbody>
</table>

† American Coal Ash Association (2013).

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**Table 4.** Summary of papers published in this special journal section on sustainable use of FGD gypsum in agricultural systems.

<table>
<thead>
<tr>
<th>General topic area</th>
<th>Title</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg and other trace elements</td>
<td>Investigation of the Potential for Mercury Release from Flue Gas Desulfurization Solids Applied as an Agricultural Amendment</td>
<td>Briggs et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Effects of Gypsum on Trace Metals in Soils and Earthworms</td>
<td>Chen et al. (2014)</td>
</tr>
<tr>
<td>Water quality</td>
<td>Impact of Flue Gas Desulfurization Gypsum Application on Water Quality in a Coastal Plain Soil</td>
<td>Torbert and Watts (2014)</td>
</tr>
<tr>
<td></td>
<td>Flue Gas Desulfurization Gypsum: Implication for Runoff and Nutrient Losses Associated with Broiler Litter Use on Pastures on Ultisols</td>
<td>Endale et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Effects of Bedding Materials in Applied Poultry Litter and Immobilizing Agents on Runoff Water, Soil Properties, and Bermudagrass growth</td>
<td>Sheng et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Hydrologic Transport of Fecal Bacteria Attenuated by Flue Gas Desulfurization Gypsum</td>
<td>Jenkins et al. (2014)</td>
</tr>
<tr>
<td>Agronomic responses and soil physical properties</td>
<td>Application of Flue Gas Desulfurization Gypsum and its Impact on Wheat Grain and Soil Chemistry</td>
<td>DeSutter et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Effects of Flue Gas Desulfurization and Mined Gypsums on Soil Properties and on Hay and Corn Growth in Eastern Ohio</td>
<td>Kost et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>In-season Effect of Flue Gas Desulfurization Gypsum on Soil Physical Properties</td>
<td>Buckley and Wolkowski (2014)</td>
</tr>
</tbody>
</table>
and mined gypsum treatments. Differences were not statistically significant except for soil Hg concentrations at the Wisconsin site. Bioaccumulation factors for nondepurated earthworms, i.e., earthworms containing gut material, were statistically similar or lower for the FGD gypsum treatments compared with controls for all elements.

**Water Quality**

There are growing concerns regarding the fate of nutrients when animal manures are land applied onto agricultural fields. The poultry industry is concentrated in the southeastern United States (USDA–NASS, 2011) and generates large amounts of poultry litter that is often used as a nutrient-rich fertilizer applied to enhance pastures and crop growth. This had led to excessive accumulation of P and other nutrients in soil. Excess nutrients, such as P, can move from treated fields to lakes and rivers, leading to algal blooms and areas of hypoxia. One approach being studied to reduce nutrient losses from manure-treated fields is to treat either the manure or soil with chemical amendments such as gypsum. Torbert and Watts (2014) used rainfall simulations to examine the impact of FGD gypsum on runoff nutrient losses from a U.S. Coastal Plains soil (Laverne sandy loam; fine, mixed, semiactive, thermic Typic Hapludults). Four rates of FGD gypsum (0, 2.2, 4.4, and 8.9 Mg ha⁻¹) were applied to plots of Coastal bermudagrass (Cynodon dactylon L.) receiving 13.4 Mg ha⁻¹ of poultry litter. Plots with 8.9 Mg ha⁻¹ FGD gypsum but no poultry litter and plots with neither poultry litter nor FGD gypsum were also used. Rainfall simulation was used to generate surface water runoff, and samples were analyzed for filtered (i.e., soluble) reactive P and Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, and Zn. Unfiltered (i.e., total) concentrations of Ca, Mg, K, Na, Fe, Mn, and Zn and traditional heavy metals As, Hg, Al, Pb, Ba, Be, Cd, Cr, Co, Cu, Pb, Ni, Si, V, Se, TI, and hexavalent Cr were also determined. Results indicated a maximal 61% reduction in soluble reactive P concentration and 51% reduction in total runoff load with the application of 8.9 Mg ha⁻¹ FGD gypsum; however, the 4.4 Mg ha⁻¹ FGD gypsum rate was almost as effective. Concentrations of heavy metals in runoff were all below detection limits.

Endale et al. (2014) also evaluated the effects of using FGD gypsum to reduce P loss and increase water infiltration under simulated rainfall events. Crusting is a typical characteristic of soils in the southeastern United States that reduces infiltration and increases runoff causing erosion and loss of soil organic matter (Hendrickson et al., 1963; Langdale et al., 1985). Previous work showed that gypsum can increase water infiltration and reduce runoff from soils prone to crust formation (Norton et al., 1993), thus affecting nutrient movement. Endale et al.’s (2014) study consisted of treatments of 0, 2.2, 4.5, and 9.0 Mg ha⁻¹ FGD gypsum combined with 13.5 Mg ha⁻¹ of broiler litter, and two controls composed of no treatments applied or a FGD gypsum and a 9.0 Mg ha⁻¹ FGD gypsum treatment without broiler litter. The treatments were applied to Coastal bermudagrass on a Cecil (Typic Kanhapudult) soil near Watkinsville, GA, and surface water runoff and nutrient (N, P, Ca, Mg) losses were evaluated. After 3 yr of treatments, a quadratic reduction in runoff was measured resulting from FGD gypsum application rate. A 30% reduction in runoff each year from the broiler litter and FGD gypsum treatment (9.0 Mg ha⁻¹) combination compared with control (no treatment) was observed. Gypsum was effective in reducing concentration and load in only one of the 2 yr: P and NH₄⁻N in 2009 (up to 83%), and NO₃⁻N in 2011 (up to 73%). Endale et al. (2014) found runoff and nutrient losses to be affected by more than just FGD gypsum applications and to include factors such as time between treatment application of FGD gypsum and broiler litter and rainfall events with sufficient intensity and amount to generate runoff, and landscape positions.

The poultry industry uses diverse types of bedding that are dependent on local availability of materials to production facilities. These bedding materials often include peanut hulls, rice hulls, hard wood shavings, pine shavings, and sawdust, among other materials. Limited information is available concerning the environmental release of nutrients from poultry litter generated from different bedding materials following agricultural land application. In a greenhouse study, Sheng et al. (2014) investigated chemical and microbial content of runoff water, soil properties, and plant growth when two poultry litter bedding materials (rice hulls and pine chips), and two nutrient immobilizing agents (gypsum and biochar) were applied to a bermudagrass sod. The FGD gypsum and biochar were mixed with poultry litter (20% w/w) and applied to a Vertic Epiaquepts soil at a rate of 9 Mg ha⁻¹. Simulated rain was applied 1, 7, 14, and 21 d post-treatment. Gypsum and biochar both significantly reduced C, N, P, Cu, and Zn losses between 24 and 38% during the first runoff event. However, only gypsum reduced these nutrient losses in succeeding events. Poultry litter containing rice hulls posed less risk for nutrient loss than did pine-chip, and gypsum addition was better than biochar for reducing C, N, P, and Cu in runoff. Although poultry litter is often applied to pastures and row crops as a plant nutrient source for N, P, and K, it can also contribute to microbial contaminants, posing public health concerns (Jenkins et al., 2006; Jenkins et al., 2008). Jenkins et al. (2014) hypothesized that if FGD gypsum increases water infiltration, reduces soil erosion, and decreases nutrient losses from animal manure applications, it may also reduce fecal bacterial contamination (i.e., *Salmonella* and *Escherichia coli*) of surface waters. They undertook two rainfall simulation experiments using 1-m by 2-m plots. Six treatments consisting of four FGD gypsum rates (0, 2.2, 4.5, and 9.0 Mg ha⁻¹) applied with 13.5 Mg ha⁻¹ poultry litter and two controls consisting of no treatments applied (no poultry litter or gypsum) and 9.0 Mg ha⁻¹ gypsum without poultry litter were evaluated. Rainfall was applied at ~64 mm h⁻¹. Flow-weighted concentrations, total loads, and soil microbial pathogens associated in runoff were determined. *Salmonella* was not detected during any of the runoff events. No significant differences between treatments were observed for *E. coli* during the 2009 rainfall simulation. In 2011, a supplemental inoculum of *E. coli* was applied to plots that received 3 yr of FGD gypsum applications. The highest FGD gypsum rate resulted in decreased flow-weighted concentrations and total loads of *E. coli*. Jenkins et al. (2014) concluded that FGD gypsum application is a management practice that reduces microbial contamination of surface waters from manure applied to agricultural fields.
Agronomic Responses and Soil Physical Properties

The Great Plains area of the United States has both sodic and acid soils that could benefit from gypsum. However, climatic conditions in this area are generally dryer than the eastern and southeastern regions of the United States, and impacts of agricultural FGD gypsum on crops and soils within the Great Plains have been limited. DeSutter et al. (2014) applied FGD gypsum and commercial gypsum at rates of 0, 2.24, 11.2, and 22.4 Mg ha\(^{-1}\) to two acid soils (pH values 4.8 and 4.9) in southwestern North Dakota and evaluated soil, wheat yields, and grain chemistry during two growing seasons. Wheat grain yields and element analysis generally were not affected by gypsum. In addition, soil element concentrations were similar across treatments at both sites during the 2 yr. More studies on high pH, sodic soils in this region are being conducted.

A study was also conducted to compare rates of FGD gypsum and commercially available agricultural (i.e., mined) gypsum as amendments on soils typical of eastern Ohio and western Pennsylvania (Kost et al. 2014). Two field experiments were conducted: one involving a mixed grass hay field and the other corn. Gypsum (two types) was applied once at rates of 0.2, 2.0, and 20 Mg ha\(^{-1}\), along with a seventh zero rate serving as the control. Corn grain yield response to gypsum was mixed, with significant differences between low and high gypsum rates in 2010. In the hay study, the low and intermediate gypsum rates generally did not result in any significant changes compared with the control treatment. At the high rate of 20 Mg ha\(^{-1}\), the first hayfield cutting (May) in 2009 and 2010 was significantly less for both mined and FGD gypsum compared with the control, but gypsum increased yields in subsequent cuttings, resulting in no significant treatment differences in total annual hay yield during 2009, 2010, or 2010 or in cumulative yield for 2008 to 2010. The FGD treatment, compared with the control or mined gypsum treatment, did not affect soil Hg concentration. However, Hg added from the FGD gypsum treatment was more available and resulted in a significantly (\(P < 0.05\)) greater Hg concentration in the hay crop compared with the control or mined gypsum treatment.

Buckley and Wolkowski (2014) surface-applied FGD gypsum to 11 Wisconsin field sites at rates of 0, 1.12, 2.24, and 4.48 Mg ha\(^{-1}\) after corn was planted. Approximately 12 wk later, penetration resistance and hydraulic conductivity were measured in situ, and samples were collected to determine bulk density and aggregate stability. No treatment effects were detected for penetration resistance or hydraulic conductivity. A positive treatment effect was observed for bulk density at only 2 of 10 sites evaluated. Aggregate stability reacted similarly across all sites and was decreased with the highest FGD gypsum application while the lower rates were not different from the control. Overall, FGD gypsum produced few beneficial effects on soil physical properties in the year of application.

Knowledge Gaps and Future Research Directions

The primary intent of this special collection is to increase knowledge among the scientific community about sustainable gypsum use in agricultural production and to establish a benchmark for future research. Informing land and resource managers of gypsum’s agroenvironmental benefits can both improve the productivity and sustainability of cropping systems and, at the same time, safeguard the environment. The research efforts described in this special collection of papers represent considerable advancements in our knowledge of gypsum use benefits.

One important conclusion from these papers is that FGD gypsum is an excellent source of Ca and S and does not pose a threat to the environment or agronomic responses of crops. Although environmental benefits have been noted when gypsum is used in agriculture, economics will ultimately be the driving force regarding gypsum’s role as a management practice. If nutrient management, especially P, becomes more problematic and regulated, gypsum may become more attractive as a practice, even in the absence of yield benefits. Utilization of FGD gypsum to intercept nutrient loss from high P soils and following manure application will also help alleviate public concerns of agriculture’s impact on water quality.

Gypsum application will not benefit all soils. Applying gypsum to sodic soils, clayey soils with poor drainage, soils containing acidic subsoils, and soils where there is deficient Ca and S will likely be most beneficial. Although yield responses have been noted with gypsum, producers will have to balance the cost and benefits of using gypsum in their crop management system. What is needed in regards to gypsum applications and crop yield responses are studies that are maintained for longer than 2 or 3 years. This is because, except for S nutrition, crop benefits from gypsum are thought to be indirect, thus requiring 3 to 5 years or more to reap yield benefits from changes in soil chemical and physical properties.

The research presented in this special collection of papers focuses mostly on the short-term impacts of gypsum and FGD gypsum on soil nutrients, metals, Hg emissions, and soluble P reductions in runoff. Some specific future, long-term research needs are summarized in Table 5. Although recent research has evaluated the use of gypsum to reduce soluble P movement from soils with high P concentrations, more research is required to determine effective gypsum rates needed to achieve the greatest P reduction in surface water runoff and its impact on P availability to cropping systems with different soil textures. Research is also needed to evaluate the impact repeated gypsum use has on nutrient leaching of base cations in sandy soils from humid climates with high rainfall to determine at what rate FGD gypsum becomes detrimental to crop production. There is a need to resolve public concerns by conducting additional risk assessments related to FGD gypsum use as a soil amendment.

Large-scale watershed studies are also needed to evaluate gypsum’s effectiveness on P loss across landscapes with different spatial variability to validate and determine if refinements are needed for current management practices that were not anticipated using small-scale controlled research plots. This will also allow more precise documentation of P reductions and provide data that could be used to model downstream P removal from the edge of fields, as well as on a farm scale. There is need for local, regional, and national exchange of scientific research to develop new and innovative uses for FGD gypsum that would be instrumental in improving soil
Table 5. Summary of knowledge gaps and future research directions FGD gypsum use.

Sulfur response studies for different row crops.

Determine the proper amount of Ca needed to beneficially impact chemical and physical properties.

Continued environmental monitoring to ensure the gypsum used does not load heavy metals in soil.

The impacts for reducing soluble P movement from fields to vulnerable water bodies.

The interaction of S and Ca with other plant nutrients.

If gypsum is indeed, increasing rooting depth and allowing plants to explore more soil volume for water and nutrients. If so, less nutrients (e.g., N) would be needed to achieve the same yields and plants would be able to withstand drought conditions longer because of greater water uptake.

Whether long-term gypsum use will increase organic and inorganic C sequestration in soil.

The ability of gypsum to reduce gaseous N losses from soil or when used as a bedding material in animal production units.

How forage quality may be improved by gypsum applications.

Separating the scientifically documented benefits from testimonials.

The economics associated with gypsum use including yield improvements, environmental changes, and overall soil quality.

The number of years required to maximize agronomic benefits from gypsum use—similar to the early years of no-tillage where initial, short-term studies often yielded negative results.

and crop productivity to maintain a supply of food and fiber for the growing population, while at the same time tying up P in soil.

Although questions remain, research results from this special collection of papers and previous research suggest that if managed properly, FGD gypsum can be used as a crop management tool to increase yields while at the same time safeguarding the environment.

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