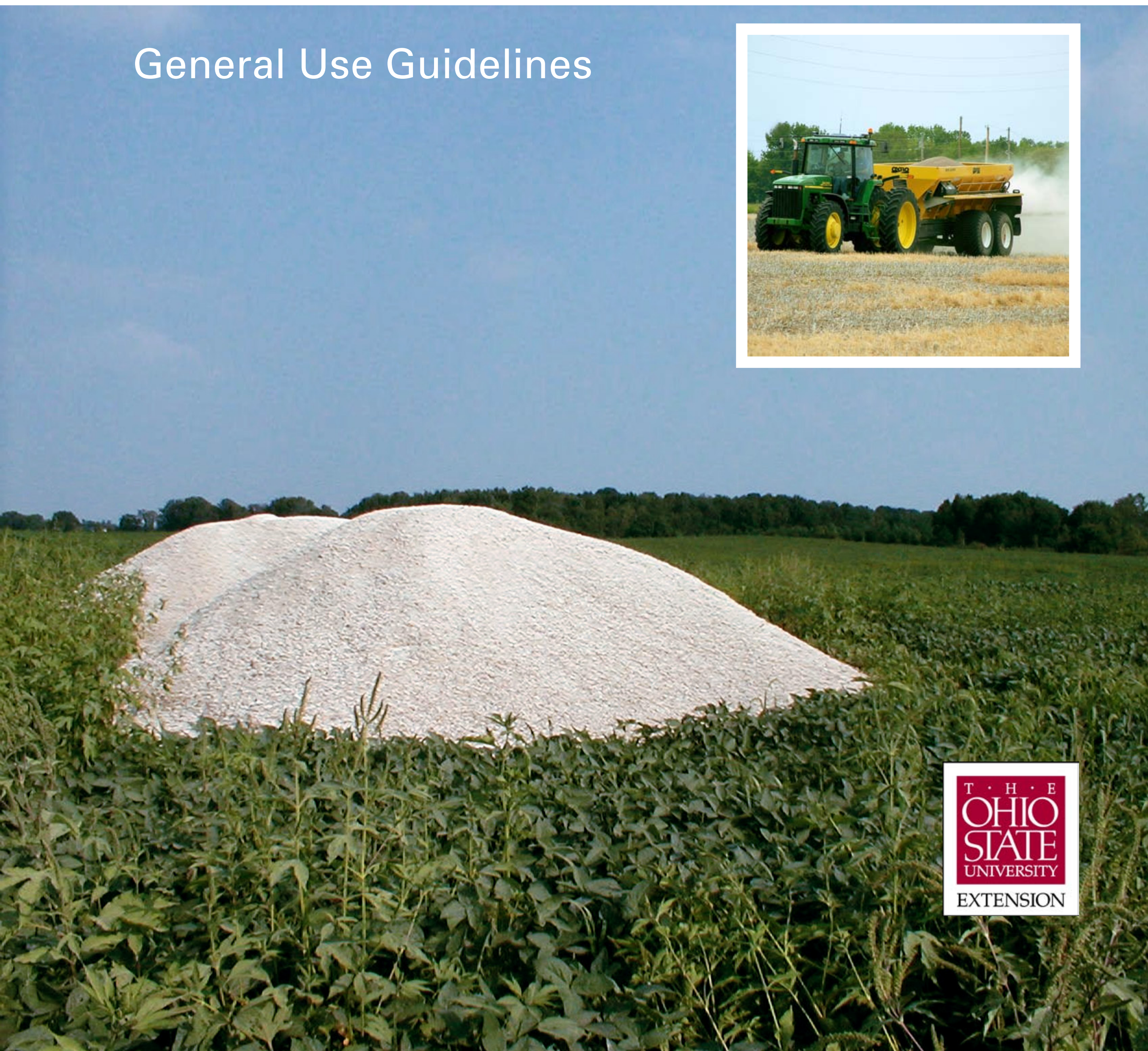
Bulletin 945

Gypsum as an AGRICULTURAL AMENDMENT

General Use Guidelines



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Contents

Preface

Gypsum is one of the earliest forms of fertilizer used in the United States. It has been applied to agricultural soils for more than 250 years. Gypsum is a moderately soluble source of the essential plant nutrients, calcium and sulfur, and can improve overall plant growth. Gypsum amendments can also improve the physical and chemical properties of soils, thus reducing erosion losses of soils and nutrient concentrations (especially phosphorus) in surface water runoff. Gypsum is the most commonly used amendment for sodic soil reclamation and can be included as a component in synthetic soils used in nursery, greenhouse, and landscape applications. These multiple uses of gypsum represent potential benefits to agricultural and horticultural users.

Currently, a large amount of flue gas desulfurization (FGD) gypsum is produced by removal of sulfur dioxide (SO_2) from flue gas streams when energy sources, generally coal, containing high concentrations of sulfur (S) are burned. Initially, most of the FGD gypsum produced in the United States was used in the wallboard industry and only a small amount was used in agriculture. However, FGD gypsum is suitable for agricultural uses and, similar to mined gypsum, can enhance crop production. As with other fertilizers and agricultural amendments, FGD gypsum must be used appropriately to avoid potential negative impacts on both agricultural production and the environment. In many respects, there are similarities between the agricultural use of FGD gypsum and nitrogen fertilizers in that both can provide crop production benefits but, if improperly used, can also lead to negative environmental impacts.

A sustainable society cannot continue to extract resources to create products and/or by-products that are then subsequently disposed of in landfills. It is imperative that recycling of all kinds of materials is encouraged and becomes more common. Agricultural applications represent important new beneficial uses for FGD gypsum. It can augment or replace commercial mined gypsum, thus avoiding both energy-intensive and water-intensive mining activities associated with gypsum extraction.

Currently there is a lack of published guidelines that provide general best management practices related to land application uses of gypsum, including FGD gypsum. To overcome this lack of information, Region 5 of the U.S. Environmental Protection Agency and The Ohio State University provided support to the authors to prepare this management guide titled *Gypsum as an Agricultural Amendment: General Use Guidelines*. An abundance of practical information related to agricultural and land application uses of FGD gypsum is included in the pages that follow. This guide is also available online at **http://ohioline.osu.edu**.

The purpose of this management guide is to provide general information about gypsum, especially FGD gypsum, as a soil amendment in Ohio as well as other places where FGD gypsum is available as a resource. This information will be useful for crop producers, soil and crop consultants, horticulturists, environmental consultants, environmental regulatory agents, and FGD gypsum producers and marketers.

CHAPTER 1 Sources and Properties of Gypsum

Gypsum is a soluble source of the essential plant nutrients, calcium and sulfur, and can improve overall plant growth. Gypsum amendments can also improve the physical properties of some soils (especially heavy clay soils). Such amendments promote soil aggregation and thus can (1) help prevent dispersion of soil particles, (2) reduce surface crust formation, (3) promote seedling emergence, and (4) increase water infiltration rates and movement through the soil profile. It can also reduce erosion losses of soils and nutrients and reduce concentrations of soluble phosphorus in surface water runoff. Chemical properties improved by application of gypsum include the mitigation of subsoil acidity and aluminum toxicity. This enhances deep rooting and the ability of plants to take up adequate supplies of water and nutrients during drought periods. Gypsum is the most commonly used amendment for sodic soil reclamation and can also be included as a component in synthetic soils for nursery, greenhouse, and landscape use. These multiple uses of FGD gypsum represent a great potential to provide benefits to agricultural and horticultural users.

Several possible sources of gypsum for agricultural use are currently available in the United States. These include mined gypsum from geologic deposits, phosphogypsum from wet-acid production of phosphoric acid from rock phosphate, recycled casting gypsum from various manufacturing processes, recycled wallboard gypsum, and flue gas desulfurization (FGD) gypsum from power plants. FGD gypsum represents a new and large volume source and is produced when coal is burned to produce electricity, heat, or other forms of energy (Figure 1-1).

Figure 1-1. Flue gas desulfurization (FGD) product is created by a scrubber that removes sulfur dioxide (SO_2) from the flue gas stream when energy sources containing high concentrations of sulfur are burned. (Norton and Rhoton, 2007.)

Combustion of coal produces 52% of our national need for electricity. During combustion, fly ash and bottom ash are produced (Figure 1-2). If the coal contains appreciable amounts of sulfur, sulfur dioxide is also produced, and the Clean Air Act Amendments of 1990 restrict sulfur dioxide emissions into the atmosphere from coal-fired facilities. This has spurred the development of flue gas desulfurization (FGD) systems that scrub the sulfur dioxide out of the flue gases and successfully bring utilities into regulatory compliance. These FGD systems can generate large quantities of products, including gypsum (Figure 1-2), which must be placed in landfills, deposited in surface impoundments, or beneficially recycled.

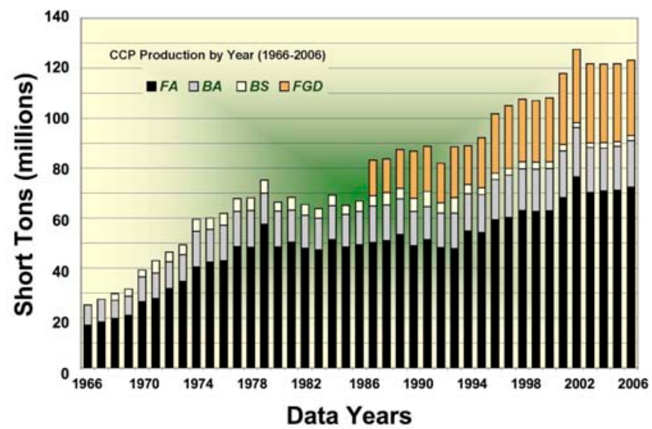

Figure 1-2. Increase of total coal combustion products (CCPs) including fly ash (FA), bottom ash (BA), boiler slag (BS), and flue gas desulfurization (FGD) materials from 1966 to 2006. (American Coal Ash Association, 2010.)

Flue gas desulfurization (FGD) gypsum is created in limestone-forced oxidation scrubbers that remove sulfur dioxide from the flue gas stream after coal combustion. In general, a wet scrubbing process first exposes the flue gases to a slurry of hydrated lime. Capture of SO_2 by the lime slurry initially forms calcium sulfite ($CaSO_3 \cdot 0.5H_2O$). Forcing additional air into the system oxidizes the calcium sulfite and converts it into gypsum, i.e., $CaSO_4 \cdot 2H_2O$ (Figure 1-3). During and after the oxidation process, washing of the by-product can remove some water-soluble elements such as boron (B). Also, in some cases, removal of fines can decrease mercury (Hg) concentrations. The final step of the process involves partial removal of water by a combination of centrifugation and vacuum filtration. The gypsum that is recovered is high quality and suitable for industrial (e.g., wallboard) and agricultural uses.

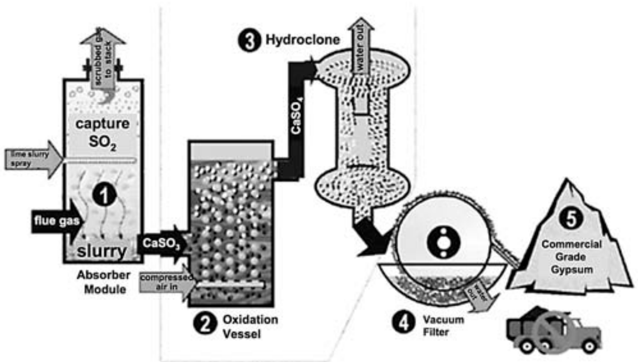

Figure 1-3. Schematic of the scrubbing process to produce FGD gypsum. (Dontsova et al., 2005.)

Production of FGD gypsum has gradually increased over the past several years (Table 1-1). In 2008, approximately 18 million tons of FGD gypsum were produced of which 60% (10.6 million tons) was used—mainly in wallboard. Less than 2% of the total FGD gypsum production was used in agriculture. However, annual production of FGD gypsum is expected to double in 10 years as more coal-fired power plants come online and as new scrubbers are added to existing power plants to comply with the EPA's Clean Air Amendments and other requirements. Existing uses of FGD gypsum will be unable to consume all of the new FGD gypsum that will be created. Because it is well known that mined gypsum can improve soil properties and water management and can enhance agricultural production, there is great interest in using the high-quality FGD gypsum produced by utilities in place of mined gypsum.

Table 1-1. FGD Gypsum Production, Total Use, and Agricultural Use from 2003 to 2008 in the United States. (American Coal Ash Association, 2010.)

Year	FGD Gypsum Production	Total Use	Agricultural Use
	Short Tons	Short Tons	Short Tons
2008	17,755,000	10,653,000	279,000
2007	12,300,000	9,228,000	115,000
2006	12,100,000	9,561,000	168,000
2005	11,975,000	9,268,000	362,000
2004	11,950,000	9,045,000	131,000
2003	11,900,000	8,299,000	33,000

Different sources of gypsum have specific mineralogical, physical, and chemical properties. Properties of FGD gypsum are often compared with results for the same measurements that are obtained for mined gypsum that is currently used in agriculture. Mineralogical and physical properties of FGD gypsum from the W. H. Zimmer Station of Duke Energy (Moscow, Ohio) and mined gypsum from the Kwest Group (Port Clinton, Ohio) are shown in Table 1-2. The mineral composition of FGD gypsum and mined gypsum is predominantly $CaSO_4{\bullet}2H_2O$. Occasionally, FGD gypsum contains minor amounts of quartz (SiO_2). Mined gypsum contains both quartz and dolomite [$CaMg(CO_3)_2$]. FGD gypsum usually possesses a much smaller and more uniform particle size (more than 95% < 150 microns) than agricultural mined gypsum that is granulated to produce a final size of 2–4 mm. However, FGD gypsum can also be processed to form larger-sized granules.

Table 1-2. Some Mineralogical and Physical Properties of FGD Gypsum from the W. H. Zimmer Station of Duke Energy (Moscow, Ohio) and Mined Gypsum from the Kwest Group (Port Clinton, Ohio). (Dontsova et al., 2005.)

Property	Unit	FGD Gypsum	Mined Gypsum
Minerals Present		Gypsum, Quartz	Gypsum, Quartz, Dolomite
Water content	%	5.5	0.38
$CaSO_4{\bullet}2H_2O$	%	99.6	87.1
Insoluble residue	%	0.4	13
Particle size			
> 250 Microns	%	0.14	100
150–250 Microns	%	3.2	0
105–150 Microns	%	33	0
74–105 Microns	%	33	0
< 74 Microns	%	31	0

The chemical composition of FGD gypsum is influenced by the type of coal, scrubbing process, and sorbent used in the desulfurization process. The FGD gypsum can have a purity as high as 99.6% (Table 1-2). Concentrations of other chemical elements in FGD gypsum from the W. H. Zimmer Station of Duke

Energy (Moscow, Ohio) and in mined gypsum from the Kwest Group (Port Clinton, Ohio) are also shown (Table 1-3).

Table 1-3. Chemical Properties of FGD Gypsum from the W. H. Zimmer Station of Duke Energy (Moscow, Ohio) and Mined Gypsum from the Kwest Group (Port Clinton, Ohio). (Dontsova et al., 2005.)

Element (Unit)	FGD Gypsum	Mined Gypsum
Plant Macronutrients		
Calcium (Ca), (%)	24.3	24.5
Sulfur (S), (%)	18.5	16.1
Nitrogen (N), (ppm)	970	
Phosphorus (P), (ppm)	< 1.0	30
Potassium (K), (ppm)	< 74	3,600
Magnesium (Mg), (ppm)	200	26,900
Plant Micronutrients (ppm)		
Boron (B)	13	99
Copper (Cu)	< 0.38	< 0.60
Iron (Fe)	150	3,800
Manganese (Mn)	0.62	225
Molybdenum (Mo)	3.2	< 0.60
Nickel (Ni)	< 3.0	< 0.60
Zinc (Zn)	1.2	8.7
Elements of Environmental Concern (ppm)		
Arsenic (As)	< 11	462
Barium (Ba)	5.5	76
Cadmium (Cd)	< 1.0	< 0.12
Chromium (Cr)	< 1.0	10.4
Lead (Pb)	< 5.0	100
Selenium (Se)	< 25	< 0.60

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CHAPTER 2

Properties of Gypsum That Provide Benefits for Agricultural Uses

To make recommendations for gypsum use in agriculture, it is important that we have a good understanding of its composition and properties. Composition of pure gypsum ($CaSO_4 \bullet 2H_2O$) is 79% calcium sulfate ($CaSO_4$) and 21% water (H_2O). Pure gypsum contains 23.3% calcium (Ca) and 18.6% sulfur (S). Gypsum is moderately soluble in water (2.5 g per L) or approximately 200 times greater than lime ($CaCO_3$). This makes the calcium in gypsum more mobile than the calcium in lime and allows it to more easily move through the soil profile.

FGD Gypsum as a Source of Plant Nutrients

For many years, crops received more than enough sulfur from rainfall, but monitoring of sulfur deposited by rainfall onto soil has revealed significant decreases in sulfur inputs. In 1979 about 31 lbs of sulfur per acre were deposited onto our soil in Ohio, and this decreased to about 16 lbs of sulfur per acre in 2007 (Figure 2-1). This decrease—coupled with other decreases in S inputs due to the use of highly concentrated fertilizers containing little or no sulfur, intensive cropping systems, and increased crop yields that result in more sulfur removal from the soil every year—is leading to more and more reports of sulfur deficiencies in crops.

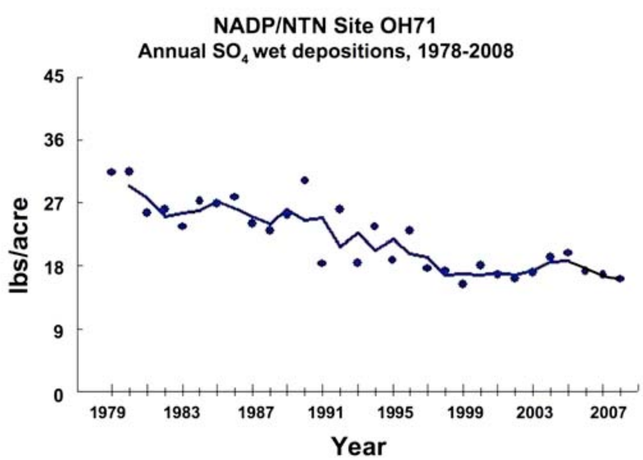

Figure 2-1. Decline of total sulfur deposition in north central Ohio (Wooster, Ohio) from 1979 to 2008. The solid line is the trend line that is evident during these years. (National Atmospheric Deposition Program, 2010.)

Gypsum is one of the earliest forms of fertilizer used in the United States. It has been applied to agricultural soils for more than 250 years. Because gypsum solubilizes rather slowly, gypsum can provide continual release of sulfur to the soil for more than just the year it is applied. Use of gypsum as a **sulfur fertilizer** to enhance crop production in sulfur deficient soils has been proved for many crops such as corn, soybean, canola, and alfalfa (Figure 2-2).

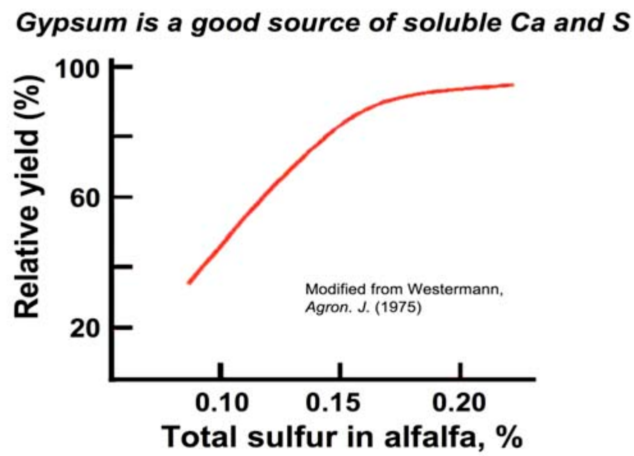

Figure 2-2. Gypsum as a sulfur fertilizer to enhance alfalfa production. Gypsum was an early form of fertilizer used in the United States and is an excellent source of calcium and sulfur.

Calcium moves very slowly, if at all, from one plant part to another, and fruits at the end of the transport system get too little. Calcium must, therefore, be constantly available to the roots. Additions to soil of a good source of calcium, such as gypsum, can improve the quality of horticultural crops (Sumner and Larrimore, Heckman, 2008; Scott et al., 1993; Shear, 1979). Root and orchard crops seem especially responsive to calcium. For example, use of gypsum as a calcium fertilizer for peanuts is well known in the southeastern United States, and adequate quantities of calcium must be present in the pegging zone for the proper development of disease-free peanuts (Figure 2-3). Root rot of avocado trees caused by *Phytophthora*, blossom-end rot of watermelon and tomatoes, and bitter pit in apples are also partially controlled by gypsum (Scott et al., 1993; Shear, 1979).

FGD Gypsum to Improve Soil Physical Properties

Soil structure is defined as the arrangement of primary mineral particles and organic substances into larger units known as aggregates with their inter-aggregate pore system. Soil structure has been shown to influence a wide variety of soil processes including water and chemical transport, soil aeration and thermal regime, erosion by wind and water, soil response to mechanical stress, seedling germination, and root penetration.

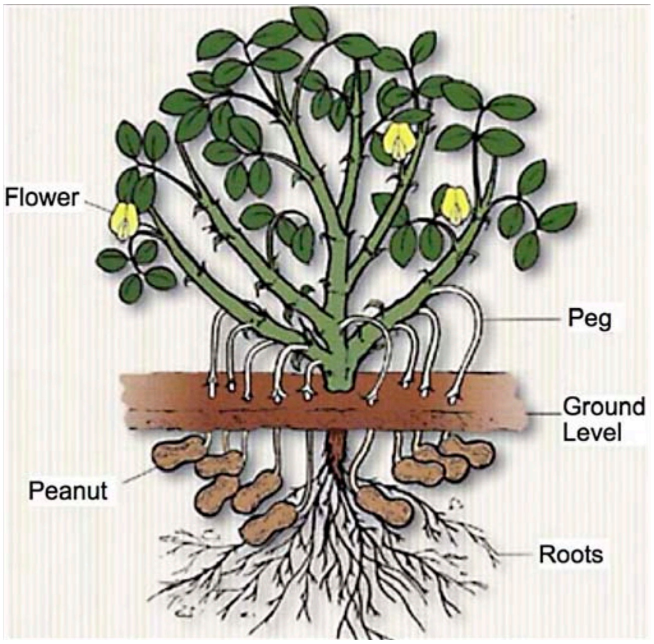

Figure 2-3. Gypsum as a calcium fertilizer to enhance peanut production. (Sumner, 2007; Tillman et al., 2010.)

Many soils from semiarid to humid regions have an unstable structure, which makes them susceptible to erosion and difficult to manage. These soils have a tendency to disperse and form a stable suspension of particles in water. As a result, they develop a more compacted structure, particularly at or near the soil surface. Clay dispersion is caused by the mutual repulsion between the clay particles (Figure 2-4), which results from the presence of extensive negative electric fields surrounding them (Dontsova et al., 2004). Flocculation is the opposite process, where the electric double layer is sufficiently compressed so that attractive forces allow coagulation of the individual clay particles into microaggregates. Application of gypsum can reduce dispersion (Figure 2-4) and promote flocculation of soils. Flocculation is a necessary condition for the formation and stabilization of soil structure. This increases water infiltration and percolation (Figure 2-5 and Dontsova et al., 2004; Norton et al., 1993; Norton, 2008), thus reducing soil erosion and improving water quality.

Soil crusting is the destruction of surface soil structure by raindrop impact, resulting in a surface layer enriched with individual soil particles and microaggregates. A serious consequence of crusting is surface sealing caused by the destruction of the interaggregate pore system in the thin layer at the interface between the soil and the atmosphere. This surface sealing reduces water infiltration and gaseous exchange with the atmosphere and can also have an adverse effect on seedling emergence (Figure 2-6).

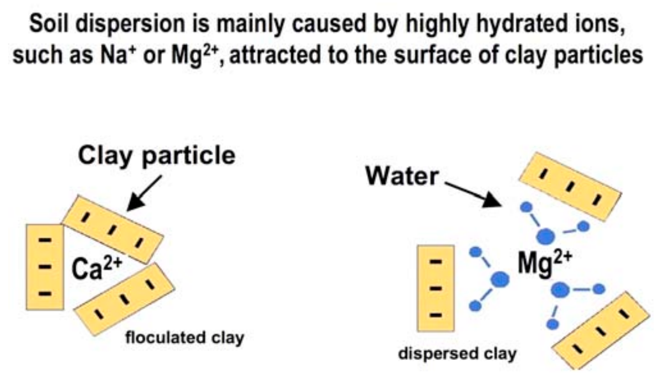

Figure 2-4. Gypsum as a soil amendment to improve soil physical properties. Addition of soluble Ca can overcome the dispersion effects of Mg or Na ions and help promote flocculation and structure development in dispersed soils. (Illustration kindly provided by Dr. Jerry Bigham, The Ohio State University.)

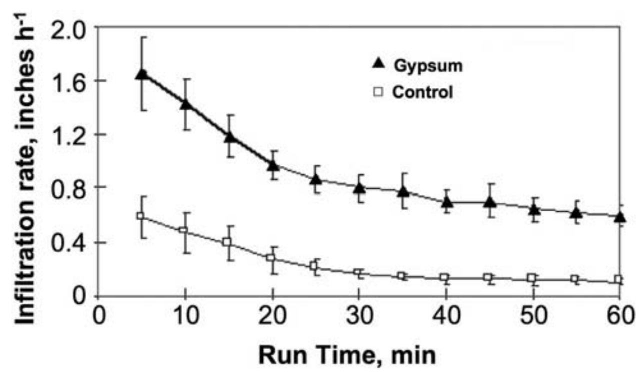

Figure 2-5. Infiltration rate for a Blount soil with and without surface-applied gypsum. Gypsum can serve as a soil amendment to improve soil physical properties and water infiltration and percolation. (Illustration kindly provided by Dr. Darrell Norton, USDA.)

Figure 2-6. Dispersion of soil particles and then surface drying creates a crust that impedes seedling emergence. Gypsum as a soil amendment can improve soil physical properties to prevent dispersion and surface crust formation. (Dontsova et al., 2005; Norton et al., 1993.)

Surface crust strength is largely dependent on clay and moisture content. Gypsum helps reduce the dispersion of the clay that leads to surface crust formation and also slows the rate of surface drying (Norton et al., 1993; Norton and Rhoton, 2007). Thus both the rate of crust development and final strength will be affected by gypsum additions leading to improved seedling emergence and establishment and in the reduction of modulus of rupture and resistance to penetration. The expected outcome of reducing soil crust formation is improved crop and pasture yields. Field studies in various locations around the world have indicated that the yields of crops can be significantly increased by gypsum, due in part to improved crop emergence and increased air and water entry into the soil.

Gypsum is the most commonly used amendment for sodic soil reclamation. The basis for this is that gypsum provides Ca that can exchange with Na and Mg, thus leading to flocculation of soil particles. This promotes better overall structure development in these highly dispersed soils so that sufficient infiltration and percolation of water into and through the soil profile can take place.

Gypsum to Improve Soil Chemical Properties

The detrimental effects on plant growth of subsoil acidity, particularly at high levels of exchangeable aluminum (Al^{3+}), are well known. The lower the soil pH, the greater the concentration of soluble and available aluminum. For many plants growing in acid soils, it is not the pH that is especially toxic, but the presence of high levels of exchangeable aluminum (Figure 2-7). Subsoil acidity prevents root exploitation of nutrients and water in the subsoil horizons. Agricultural lime is recommended for correction of soil acidity and low soil pH. Whereas the beneficial effects of calcitic lime are mostly limited to the zone of incorporation, surface applications of gypsum may affect soil physical and chemical properties at depth. This is because of gypsum's much greater solubility compared to lime (Figure 2-8).

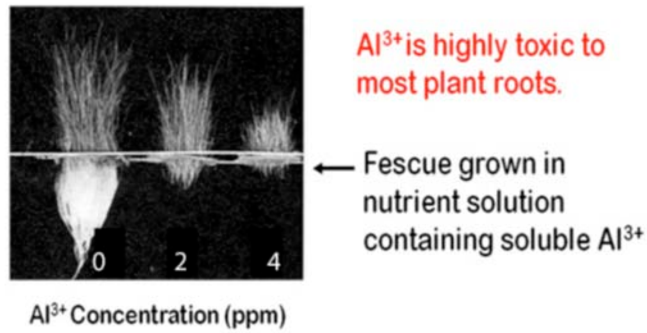

Figure 2-7. Effects of aluminum (Al^{3+}) on growth of fescue. (Illustration adopted from Buckman and Brady (1969) and kindly provided by Dr. Jerry Bigham, The Ohio State University.)

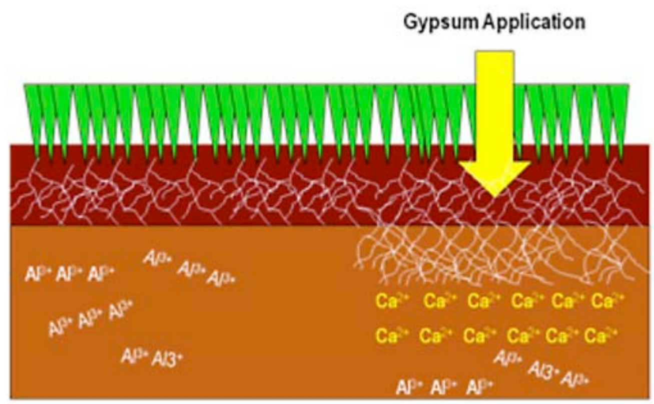

Figure 2-8. Gypsum as a soil amendment to remediate subsoil acidity. Gypsum is 200 times more soluble than lime and calcium and sulfur movement into soil profiles is enhanced by the addition of gypsum. (Sumner and Larrimore, 2006.)

Gypsum applications to Ca-deficient soils in humid regions have shown beneficial effects because of Ca movement into the subsoil (Figure 2-9 and Farina and Channon, 1988; Stehouwer et al., 1999; and Toma et al., 1999), thereby improving root growth and lowering water stress. This improvement in crop response to gypsum use in soils with acid subsoils is not due to a

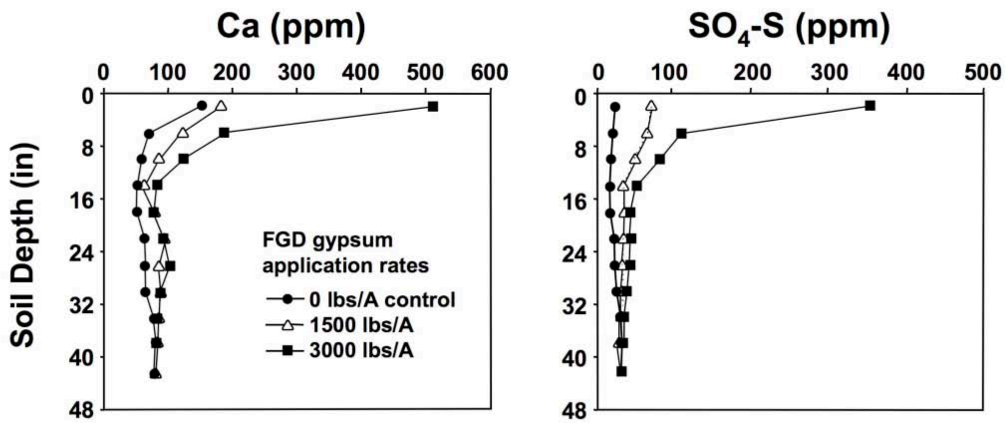

Figure 2-9. Calcium and sulfur movement into soil profiles is enhanced by the addition of gypsum. These data were obtained six months after gypsum application. (Chen et al., 2005.)

change in pH, as gypsum is a neutral salt and not a liming agent. Therefore, its effect on surface or subsoil pH is relatively modest. However, FGD gypsum can ameliorate the phytotoxic conditions arising from excess soluble aluminum in acid soils by reacting with Al^{3+}, thus removing it from the soil solution and greatly reducing its toxic effects (Figure 2-10 and Shainberg et al., 1989; Smyth and Cravo, 1992). Overcoming the effects of subsurface aluminum toxicity leads to improved deep rooting (Figures 2-8, 2-10, and 2-11) so that crops can take up water and nutrients from subsoil layers. This can greatly increase the supply of water and nutrients to crops. This is especially important in the dry season of arid areas, and a positive response to FGD gypsum is often greatest in moisture stress conditions.

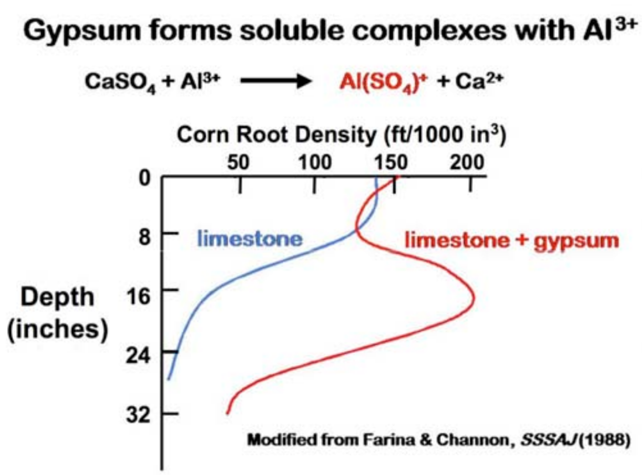

Figure 2-10. Soluble aluminum (Al^{3+}) is toxic to plants. Gypsum can react with Al^{3+}, thus removing it from the soil solution and greatly reducing its toxic effects on plant roots. (Illustration kindly provided by Dr. Jerry Bigham, The Ohio State University.)

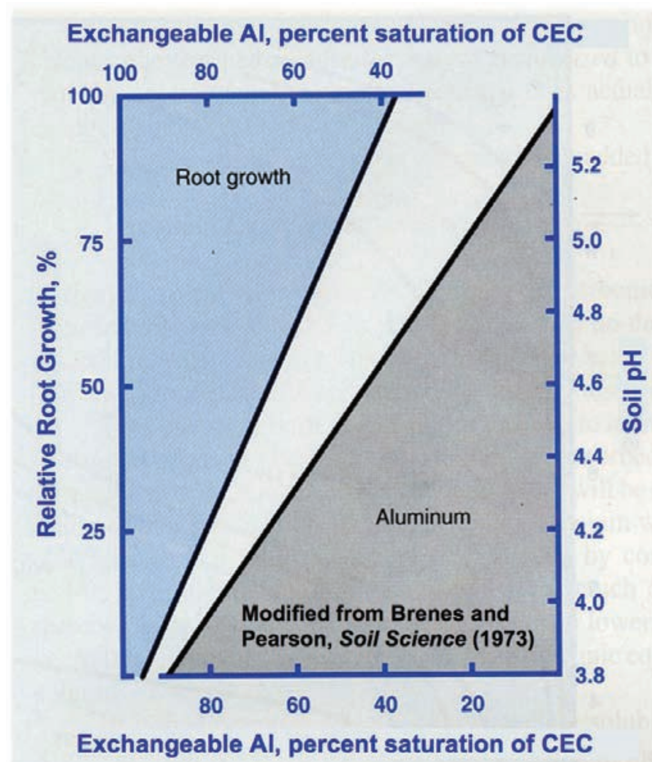

Figure 2-11. Removal of subsoil acidity due to Al^{3+} can promote deeper rooting of plants. (Illustration kindly provided by Dr. Jerry Bigham, The Ohio State University.)

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CHAPTER 3

Agricultural and Land Application Uses of Gypsum

Application of mined gypsum to agricultural soils has a long history (Crocker, 1922). Most farmers do not have experience in applying gypsum to their fields and do not know the value of gypsum. Also, information is lacking as to the best management practices associated with using gypsum as an agricultural amendment. In this chapter, several specific examples of using gypsum in agriculture and for other land applications are introduced and briefly described. As previously mentioned in Chapter 1, a readily available source of gypsum for agricultural use in Ohio and the United States is FGD gypsum.

Gypsum as a Source of Plant Nutrients for Crops

An experiment was conducted in Ohio from 2002 to 2005 to test a sulfur-by-nitrogen nutrient interaction for corn production. The nitrogen was applied at rates of 0–210 lbs per acre as ammonium nitrate (NH_4NO_3) and sulfur was applied as FGD gypsum or another FGD product at the rate of 30 lbs per acre. Results indicated sulfur application significantly ($P \leq 0.05$) increased the yield of corn compared to the no-sulfur control treatment in 2003 (Table 3-1). There was a sulfur-by-nitrogen interaction in 2004 and 2005 with sulfur increasing relative yields more at the low nitrogen application rates than at the high nitrogen rates. This result suggests that reduced nitrogen inputs and increased yield could offset the cost of applying gypsum and would also diminish the potential for nitrate contamination of surface and ground waters.

Table 3-1. Effects of Nitrogen and Sulfur (S) Fertilizers on Corn Yields Grown in Wooster Silt Loam from 2003 to 2005. (Chen et al., 2008.)

Nitrogen	2003		2004		2005	
	No S	30 lbs S/acre	No S	30 lbs S/acre	No S	30 lbs S/acre
lbs/acre	bushels per acre					
0	127	149	105	122	66	61
60	161	180	139	149	67	90
90	162	181	148	158	76	85
120	185	192	161	190	89	132
150	184	193	170	167	118	111
180	190	206	172	162	99	84
210	194	199	186	168	86	93

Agricultural gypsum and two types of FGD products that contain calcium sulfate ($CaSO_4$) and calcium sulfite ($CaSO_3$) were applied at 0, 14, and 60 lbs of sulfur per acre to an agricultural soil (Wooster silt loam) located near Wooster, Ohio. Growth of a new planting of alfalfa (*Medicago sativa* L.) was increased 10 to 40% by the treatments compared to the untreated control (Chen et al., 2005). Also at Wooster, increased alfalfa growth of 18% was associated with additions of gypsum for the combined years of 2000–2002 (Figure 3-1). In a further study, mined gypsum and the FGD products mentioned earlier were applied at 0, 7, 14, and 21 lbs of sulfur per acre to five established alfalfa stands in different regions of Ohio. Mean alfalfa yields were increased 4.6% in 2001 and 6.2% in 2002 with sulfur treatments compared to the untreated control. These results were statistically significant at the $P \leq 0.05$ level (Chen et al., 2005).

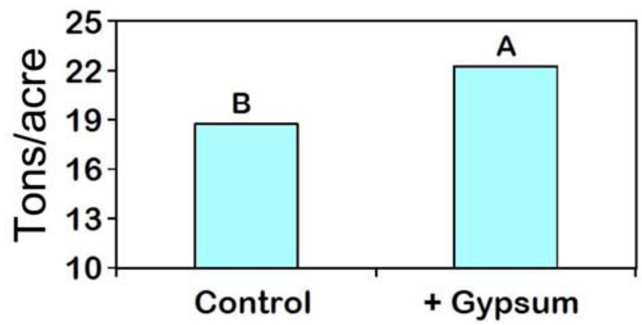

Figure 3-1. Yields of alfalfa at Wooster, Ohio, (cumulative yields for years 2000–2002) were increased by the addition of gypsum, which improved the sulfur nutritional status of the soil. Different letters over each bar represent a significant difference at $P \leq 0.05$.

Gypsum can also affect yields of other crops, and gypsum has been the most common calcium source for improving peanut production in the southeastern United States. Application of gypsum not only increases peanut yield but also improves peanut quality. A study in Florida indicates that application of gypsum at 0.5 ton per acre significantly increases the yield and value of peanuts and the calcium concentration in peanut seeds (Table 3-2).

Table 3-2. Effect of FGD Gypsum on the Yield, Value, and Calcium (Ca) Content of Peanuts Grown in Florida. (Sumner and Larrimore, 2006.)

Gypsum	Yield	Value	Seed Ca
tons/acre	lbs/acre	$/acre	%
0	3,280	540	0.021
0.5	3,940	649	0.034

Gypsum to Improve Soil Physical Properties

Gypsum has been shown to improve surface infiltration rates by inhibiting or delaying surface seal formation as was described in the previous chapter. A field study was conducted using FGD gypsum at 1–2 tons per acre to improve infiltration in a poorly drained soil in Indiana, and the result is shown in Figure 3-2 (Norton and Rhoton, 2007). There was greater ponding of water in the control field than in the FGD gypsum-treated field. Water ponding restricts air exchange with the atmosphere and leads to poor crop stand.

Figure 3-2. Application of FGD gypsum increases water infiltration and percolation. Foreground is the gypsum application section, and background is the control section. (Norton and Rhoton, 2007.)

Gypsum application to soil can reduce soil erosion by flocculating clay particles so that they settle out of surface water and thus are less prone to be moved offsite. Many soils in the United States have also become highly enriched in soluble phosphorus. This occurs on soil surrounding animal production facilities when heavy applications of manure or fertilizer phosphorus are applied without proper soil testing. This phosphorus, if moved off the field into receiving water bodies, can cause eutrophication, which is defined as excessive nutrients in a lake or other body of water. The calcium in gypsum can bind with phosphorus to form a calcium phosphate precipitate and thus help improve water quality (Favaretto et al., 2006). Of several treatments to reduce phosphorus in surface water runoff, gypsum at approximately 2.0 tons per acre was found to be the most effective and cost efficient (Figure 3-3 and Stout et al., 2000). It has been suggested that use of gypsum, including FGD gypsum, could be included in a best management plan (BMP) for nutrient management of manures from large animal production facilities.

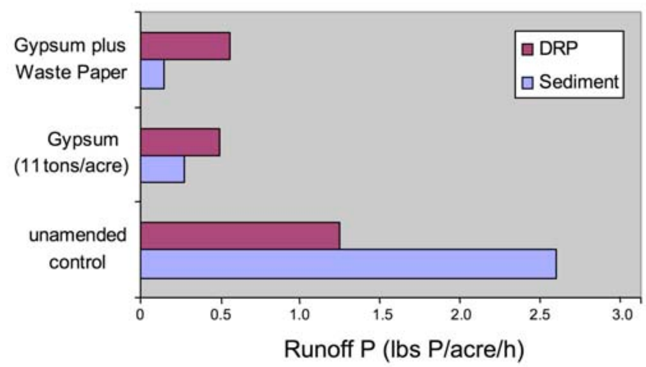

Figure 3-3. Effect of gypsum on runoff phosphorus. DRP is dissolved reactive phosphorus. (Brauer et al., 2005.)

Gypsum to Improve Soil Chemical Properties

A study in Brazil indicated that applications of gypsum into the plow layer reduced subsurface aluminum toxicity and improved deep rooting so that water and nutrient uptake by corn, wheat, soybean, sorghum, and leuceana (a forage legume) were dramatically improved (Ritchey et al., 1995). For example, the percentage of corn roots found below 45-cm depth increased by more than 600% with the addition of 2.7 tons per acre or more of gypsum. Corn, wheat, sorghum, and leuceana yields were also increased by 45, 50, 24, and 50% over the control, respectively. A study in Mississippi indicated that application of FGD gypsum at 4.4 tons per acre ameliorated subsoil acidity and increased cotton yield (Table 3-3) and overall cotton quality. Work in South Africa on corn has also shown yield benefits when gypsum was applied to help overcome subsoil acidity problems (Farina et al., 2000a; 2000b).

Gypsum is the most commonly used amendment for sodic soil reclamation. A field study was conducted in China using gypsum to remediate a heavy sodic soil.

Very few crops could grow on the site before reclamation in 2000. Gypsum was applied in 2001 at a rate of 26 tons per acre, and corn was planted in 2002 and 2003. Figure 3-4 shows the growth of corn plants in the section treated with gypsum (background) and in a section of the control treatment (foreground).

Table 3-3. Effect of FGD Gypsum on the Yield of Cotton in an Acid Subsoil in Mississippi. (Sumner and Larrimore, 2006.)

Gypsum Treatment	Seed Cotton	Lint
tons/acre	lbs/acre	
0	1,660	612
4.4	1,990	729

Figure 3-4. Gypsum as a soil amendment to remediate sodic or sodium-affected soils. Foreground is the control section, and background is the gypsum application section. (Xu, 2006.)

Gypsum for Nursery, Greenhouse, Landscape, and Sports Field Use

As a Component of Plant Growth Media

In 2004, we combined FGD gypsum, bottom ash, and composts to create high-quality, low-cost marketable growth media for the nursery and landscape industries. Figure 3-5 shows tomato (*Lycopersicum esculentum*) seedlings 35 days after planting when grown in a commercial medium compared to the medium containing gypsum, peat, compost, and bed ash (Bardhan et al., 2005). The result indicated that the medium containing FGD gypsum significantly enhanced the growth of tomato compared to the commercial medium.

Figure 3-5. FGD gypsum as a component of synthetic soils for nursery and greenhouse use. Tomato seedlings in the left pot were growing in a commercial medium, and those in the right pot were growing in the medium containing FGD gypsum.

In 2004, we created a mix containing 20% FGD gypsum, 33% bottom ash, 12% biosolids, 23% dairy manure compost, and 12% sphagnum peat. This medium was used to test for nursery growth of red sunset maple trees in a pot-in-pot production system. The goal was to produce healthy and marketable nursery crops with minimum potential negative environmental impacts. The mix containing FGD gypsum was compared with commercial mixes at the Willoway Nursery site in Avon, Ohio. In this study, the growth of maple trees in the mix containing FGD gypsum was not better, but similar, to that in the commercial mixes.

Gypsum for Landscape and Sports Field Use

Turfgrasses are perennials, and turf management often needs to ameliorate the effects of acidity that can accumulate in the soil profile due to nitrogen fertilizer. However, agricultural lime only corrects acidity in the application layer. It cannot ameliorate the effects of subsoil acidity without tilling the soil in which the turf is growing. Surface application of gypsum, which is more soluble than agricultural lime, can provide calcium and sulfur for grasses and ameliorate aluminum (Al^{3+}) toxicity experienced by the grasses growing in soils that often become acid because of high nitrogen fertilizer inputs. An experiment conducted at Pennsylvania State University indicated that green cover was increased 6% by FGD gypsum applied at a rate of 7 tons per acre (Schlossberg, 2006). Figure 3-6 shows FGD gypsum being surface-applied to a golf course.

Figure 3-6. FGD gypsum being applied to the soil surface of a golf course. (Sumner and Larrimore, 2006.)

Other Uses of Gypsum in Agriculture

A report by Dick et al. (2006) summarizes 20 different potential agricultural and other land application uses of gypsum. As previously noted, gypsum has been used to enhance the yield and quality of some horticultural crops. For example, gypsum decreases storage rots of cantaloupe and tomato (Sumner and Larrimore, 2006; Scott et al., 1993; Shear, 1979). One study in Georgia found that application of FGD gypsum at the rate of 1,000–3,000 lbs per acre increased cantaloupe growth, fruit yield, skin calcium, and storage time (Sumner and Larrimore, 2006). A study in Mississippi and Alabama indicated that application of gypsum at 4,000 lbs per acre increased tomato yield by 20% and increased shelf life.

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CHAPTER 4

Gypsum Application

Determining the Appropriate Application Rate

In order to make efficient use of gypsum to enhance crop production, it is necessary to be able to determine the amount of gypsum that should be applied. The rate of gypsum application depends on the specific purposes for using gypsum for crop production and the farmer's perception of return on investment. This is primarily a factor of increased revenue obtained due to increasing crop yields or improving fertilizer use efficiency relative to the cost of transport and application of the gypsum.

For many land-application uses of gypsum, it is important that the recommended rates are based on well-defined principles of soil and agronomic science. If the source of gypsum is FGD gypsum, application at a rate greater than predicted necessary may be interpreted as disposal and could also be harmful. This is similar to other types of agricultural inputs, such as nitrogen fertilizer, if applied at excessive rates. Application at a rate less than that predicted as necessary may be ineffective for enhancing crop yields or improving soil quality. According to the specific purpose for why gypsum is to be applied to soil, the appropriate rates can vary greatly, from less than 100 lbs to several tons per acre each year.

Application Rates of Gypsum as Sulfur Fertilizer to Enhance Crop Production

Gypsum is a quality source of both calcium and sulfur for plant nutrition. Deficiencies of sulfur in crops are increasing due to a combination of factors (Dick et al., 2006). These factors include increased crop yields that result in more sulfur removal from soil, reduced sulfur inputs contained as by-products in other nutrient fertilizers, and decreased sulfur deposition from the atmosphere. Sulfur removed by various crops at specific yields is presented in Table 4-1. Availability of sulfur to crops from soil is reduced due to plant removal, and additional sulfur may need to be added to soil for improved growth of rotational crops.

Plant testing has been used to assess the nutrient status of crops. Sulfur concentrations in crop tissues are usually decreased due to sulfur deficiency of the crop. Critical sulfur concentrations in crop plants are listed in Table 4-2. Critical levels will probably not be useful for correcting sulfur nutritional needs in the current crop because of the difficulty of getting back in the field in a timely manner to correct the sulfur deficiency. However, this information is important because it can help identify soils that are low in available sulfur and guide decisions about sulfur fertilizer needs in crops for the next year.

Another way to identify soils that may be deficient in sulfur is through the application of a sulfur deficiency model. A database of the sulfur status of Ohio's soils for crop growth was developed by combining inputs from the atmosphere and organic matter with outputs due to leaching and crop removal. The database is organized by soil series within counties to predict the sulfur status of a particular soil for crop growth. Potential availability of sulfur to crops from soil can be predicted using the model. This model can be found at **http://www.oardc.ohio-state.edu/sulfurdef**. It is easy to use and a good tool to rapidly determine whether a soil may be deficient in available sulfur and thus limit crop production. However, confirmation by on-farm trials and/or crop tissue analysis is recommended. Details on how to conduct on-farm fertility trials have been provided by Sundermeier (1997).

Table 4-1. Harvest Removal of Sulfur (S) by Various Crops at Specific Yields and the Amount of Gypsum Needed to Replace the Removed Sulfur. (Dick et al., 2008.)

Crop	Yield	S Removed	Gypsum Application to Replace S Removed
	tons/acre	lbs/acre	lbs/acre
Corn grain	5.8	15	81
Sorghum forage	4.2	22	118
Wheat	2.4	7	38
Canola	1.0	12	65
Soybean	1.8	12	65
Sunflower	1.7	6	32
Alfalfa	5.8	30	161
Cool-season grass	4.0	16	86
Cotton	0.8	40	215
Peanut	2.0	21	113
Rice	3.5	12	65
Sugar beet	30	45	242
Orange	27	28	151
Tomato	30	41	220
Potato	25	22	118

Suggested application rates of gypsum as a fertilizer source of sulfur for specific crop requirements are listed in Table 4-3. These rates are based upon combining inputs from the atmosphere and organic matter with outputs to leaching and crop removal. If gypsum is applied as a calcium fertilizer instead of as a sulfur fertilizer—for example, to enhance the yield and quality of horticultural crops and especially root crops such as peanut—application rates can be as much as 1,000–4,000 lbs per acre (Sumner, 2007).

Concentrations of sulfur and calcium in gypsum usually range from 17–19% sulfur and 20–24% calcium. The amounts of these nutrients that are added to soil at different application rates of gypsum (Table 4-4) are based on values of gypsum having 18.6% sulfur and 23.3% calcium.

Table 4-2. Critical Sulfur Concentrations in Crop Plants. (Dick et al., 2008.)

Crop	Part Sampled	Time of Sampling	Concentration			
			Deficient %	Low %	Sufficient %	High %
Alfalfa	Top 15 cm	Early bud	< 0.20	0.20–0.25	0.26–0.50	> 0.50
Corn	Ear leaf	Silking	< 0.10	0.10–0.20	0.21–0.50	> 0.50
Oats	Top leaves	Boost stage	< 0.15	0.15–0.20	0.21–0.40	> 0.40
Soybean	First trifoliate	Early flower	< 0.15	0.15–0.20	0.21–0.40	> 0.40
Barley	YEB†	Mid-late tillering			0.15–0.40	
Canola	YMB	Prior to flowering			0.35–0.47	
Cotton	YMB	Early flowering			0.20–0.25	
Ryegrass	Young herbage	Active growth			0.10–0.25	
Peanut	YML	Pre-flowering			0.20–0.35	
Sugar cane	Top visible dewlap	Active growth			0.12–0.13	
White clover	Young herbage	Active growth			0.18–0.30	
Wheat	YEB/YMB	Mid-late tillering			0.15–0.40	
Rice	Whole top	Maximum tillering			0.14	
Rice	Whole top	Active tillering			0.23	

†YEB, youngest emerged leaf blade; YMB, youngest mature leaf blade; and YML, youngest mature leaf.

Table 4-3. The Amount of Gypsum Application Needed to Supply Specific Amounts of Sulfur Nutrient to Support the Growth of Various Crops. These Suggestions Are Broadly Based on the Amount of Sulfur Removed at Harvest and Lost Due to Leaching.

Crop	Amount of Sulfur Application	Amount of Gypsum Application
	lbs/acre	lbs/acre
Corn grain	30	160
Sorghum forage	40	220
Wheat	30	160
Canola	30	160
Soybean	30	160
Sunflower	15	80
Alfalfa	70	380
Cool-season grass	30	160
Cotton	100	540
Peanut	50	270
Rice	30	160
Sugar beet	100	540
Orange	60	320
Tomato	100	540
Potato	50	270

Table 4-4. Application Rates of Sulfur (S) and Calcium (Ca) Calculated Based on the Amount of Gypsum Application.

Gypsum	S	Ca
lbs/acre	lbs/acre	lbs/acre
50	9.3	12
100	19	23
1,000 (0.5 ton)	186	233
2,000 (1.0 ton)	372	466
5,000 (2.5 tons)	930	1,165
10,000 (5.0 tons)	1,860	2,330
15,000 (7.5 tons)	2,790	3,495
20,000 (10 tons)	3,720	4,660

Application Rates of Gypsum as a Soil Amendment to Improve Physical and Chemical Properties of Soils

Gypsum can provide many physical and chemical benefits to soil in addition to nutritional benefits. In some soils it can: (1) prevent dispersion of soil particles, (2) reduce surface crust formation, (3) promote seedling emergence, (4) increase water infiltration rates and movement into and through the soil profile, (5) reduce erosion losses of soils and nutrients and phosphorus concentrations in surface water runoff, and (6) mitigate subsoil acidity and aluminum toxicity.

An easy test to see if gypsum will physically benefit a soil is to take a teaspoon of soil and one-half ounce of distilled or rain water in a small tube. Alternatively, one can place two tablespoons of soil in a straight-walled quart jar and fill it two-thirds full with water. Shake up the soil in the water and then allow it to stand for two or more hours. If the upper liquid remains cloudy after two hours, the soil is likely to respond to an application of gypsum. Application rates of gypsum for improving soil physical properties are usually in the range of 1,000 to 5,000 lbs per acre (Brauer et al., 2006; Norton and Rhoton, 2007). In some extreme cases, such as for sodic soils, higher rates may be justified.

Gypsum can also be used to improve the chemical properties of a soil. Predictions for the gypsum requirement (GR) for remediating subsoil acidity, magnesium-impacted soils, and sodic soils may be obtained using the equations shown in Table 4-5. For these applications, higher rates are often recommended than for overcoming nutrient deficiencies because the calcium (primarily) needs to exchange with sodium or magnesium or leach downward to replace aluminum. The calcium cannot be easily supplied by agricultural lime since the solubility of agricultural lime is 200 times less than that of gypsum. Also, in the case of sodic soils, the pH is already very high and an upward pH adjustment is not needed. For remediating acidity in acid subsoils (20–60 cm depth), application rates of gypsum usually vary from 2 to 10 tons per acre. For remediating magnesium-dominated soils, application rates of gypsum usually range from 2 to 5 tons per acre. Typical application on sodic clay soils ranges from 1 to 5 tons per acre every few years as needed. Gypsum may need to be reapplied every couple of years in wet climates or on irrigated fields as the gypsum will leach out of the soil profile.

Table 4-5. Equations to Estimate the Gypsum Requirement (GR) for Remediating Subsoil Acidity, Magnesium Soils, and Sodic Soils.

Amendment	Equation*	Source
Subsoil Acidity Amendment	GR (lbs/acre) = $(-114 + 82.773A_s - 2.739A_s^2) \times 0.893/0.186$	Ritchey et al., 1995
Magnesium Amendment	GR (lbs/acre) = [(% Mg base saturation – 20)/100 × CEC × 2000] + [(pH –7.2) × 2000] or GR (lbs/acre) = [(((ppm Mg/120)/CEC) – 0.20) × CEC × 2000] + [(pH –7.2) × 2000]	Hecht, 2006
Sodium Amendment	GR (lbs/acre) = [(((ppm Na/230)/CEC) – 0.02) × CEC × 2000] + = [(((ppm Mg/120)/CEC) – 0.20) × CEC × 2000] + [(pH –7.2) x 2000]	Hecht, 2006

*A_s = (S sorbed)/(S in solution) after 2 grams of soil are shaken for 18 h with 20 mL of 0.75 mM $CaSO_4 \cdot 2H_2O$ solution. CEC is cation exchange capacity (meq/100g).

Application Rates of Gypsum for Nursery, Greenhouse, Landscape, and Sports Field Use

Use of gypsum for nursery, greenhouse, landscape, and sports fields is generally based on the same physical and chemical properties as for agronomic crops. However, rates used are generally higher due to the inability to till the gypsum into the soil and to avoid annual or multiple applications. Application rates can vary greatly, from 5 to 20% of the medium for nursery and greenhouse crops and from 4,000 to 14,000 lbs per acre for landscape and sports turf fields (Bardhan et al., 2004; Schlossberg, 2007).

Summary of Recommended Gypsum Application Rates for Various Uses

Recommended rates, time of application, and method of application of gypsum for various functions are summarized in Table 4-6. For use of gypsum as a nutritional source of sulfur and calcium, application should be done annually. However, for some applications, especially where the higher rates are used, it is very likely that application will not be done annually. Instead application will occur initially at a high rate to remediate a soil situation, and then, in subsequent years, much lower maintenance rates would be applied.

Equipment and Other Land Application Considerations for FGD Gypsum

The method of applying gypsum to soil or for other agricultural uses depends on the reason the gypsum is being used. Usually, gypsum can be spread as either a solid or dissolved in irrigation water if ground to a fine powder. For land application, gypsum sources in the form of either a powder or granule can be applied directly to the soil surface using conventional dry material spinners or drop box spreaders (Figure 4-1). In cases where the gypsum is in a powder form, application during strong windy days should be avoided. If the desire is to move the gypsum downward into the subsoil as quickly as possible and if there is a need to avoid and decrease erosion by wind and water, the gypsum should be immediately incorporated into the soil.

Figure 4-1. FGD gypsum can be applied directly to the soil surface using conventional dry material spreaders. (From the FGD Network website: http://www.oardc.ohio-state.edu/agriculturalfgdnetwork.)

The time of application will also be different depending on the reasons or benefits that are desired for the use of gypsum. In reality, gypsum can be applied during any season of the year, but other considerations dictate the best times for application. Autumn applications can be made as soon as crops are harvested from the field. Autumn applications provide several advantages compared to other seasons. The fields are generally drier, making it easier to drive heavy spreading equipment across the field without damaging the soil. An autumn application allows time for soil/gypsum reactions to take place so that the next year's crop can better take advantage of the gypsum application.

In some cases, dissolving gypsum in irrigation water is a preferred method of application for agricultural uses. However, for gypsum to go readily into solution, it must be finely ground to less than 200 to 300 mesh size. Application by water offers many benefits including (1) increasing the solute concentration of irrigation water to enhance water infiltration into soil, (2) decreasing the sodium absorption ratio (SAR) of saline irrigation water so that the irrigation water does not contribute to the sodicity of the soil by increasing the exchangeable sodium percentage, (3) avoiding unsightly granules of gypsum lying on turf of golf courses, (4) promoting soluble calcium to fruit crops and other plants to avoid low calcium fruit disorders like blossom end rot in tomatoes and bitter pit in apples, (5) decreasing the length of time for soils to respond to gypsum application, and (6) increasing the uniformity of the gypsum application (Nature's Way Resources, 2010).

If the soil has cracks, applying gypsum in irrigation water will allow the gypsum to penetrate further into the soil. The result will be that the effects of the application will be noted more rapidly and also will occur deeper into the soil profile.

Table 4-6. Rate, Time, and Method of Application of Gypsum for Various Functions.

Function	Suggested Rates of Application (lbs/acre)			Suggested Time of Application	Suggested Application Method	Reference
	Low	Normal	High			
Sulfur fertilizer to enhance crop production	100	300	500	Before planting	Soil surface or incorporated	Chen et al., 2008 DeSutter and Cihacek, 2009
Calcium fertilizer to enhance crop production (especially root crops, e.g., peanuts)	1,000	2,000	4,000	Before peanut pegging	Soil surface	Grichar et al., 2002
Soil amendment to remediate subsoil acidity	3,000	6,000	10,000	1–180 days before planting	Soil surface	Chen et al., 2005
Soil amendment to remediate sodic or sodium-affected soils	2,000	10,000	20,000	90–180 days before planting, before rainy season	Soil surface or incorporated	Xu, 2006
Soil amendment to improve water quality (e.g., by reducing phosphorus concentrations in surface water runoff)	1,000	6,000	9,000	1–180 days before planting	Soil surface	Norton and Rhoton, 2007
Soil amendment to improve soil physical properties and water infiltration and percolation	1,000	3,000	9,000	1–180 days before planting	Soil surface	Sumner, 2007
As a lawn care product and sport field application	4,000	8,000	14,000	Spring, summer, or autumn	Soil surface	Schlossberg, 2007
As a component of synthetic soils for nursery	5%	10%	20%	Preparation of synthetic soils	Mixing with other components	Bardhan et al., 2004

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CHAPTER 5

Economic Considerations Related to Gypsum Use

The relationship between costs and benefits, or the cost/benefit ratio, is an important consideration for whether use of gypsum as a soil amendment will be adopted or sustained. The costs associated with using gypsum, including FGD gypsum, includes the costs of purchasing the material, transporting it from the site of generation to the site of use, and spreading it on the land. The benefits are most often associated with increased crop yields.

A preliminary economic survey of eight farmers was conducted in northwestern Ohio. The farmers were selected as pairs, with one farmer in each pair using no-tillage and approximately one ton of gypsum per acre as part of the crop production system and the other nearby farmer on the same soil type using conventional tillage practices without gypsum. The survey was conducted at the end of two cropping years, and the costs of production and return above total costs were calculated in 2005. The results (Table 5-1) can compare these two cropping systems but cannot unequivocally attribute all of the differences to either only no-tillage or only gypsum. The differences in return above total cost were primarily attributed to lower costs, and not crop yield, associated with the NT plus gypsum crop production system compared to the CT minus gypsum crop production system. More research is needed to determine the best soil types and management practices that lead to potential benefits of using gypsum as a soil amendment for enhancing crop yield and farm profitability.

Table 5-1. Total Costs and Return Above Total Costs for Two Different Management Systems (NT—no tillage and CT—conventional tillage) for Corn and Soybean Production. (Chen et al., 2005.)

Crop	Management System	Total Cost ($/acre)[a]	Return Above Total Cost ($/acre)[b]
Corn	NT plus gypsum	321	17
	CT minus gypsum	374	–28
Soybean	NT plus gypsum	228	79
	CT minus gypsum	272	18

[a] Includes fuel, machinery and equipment, land costs, management costs and labor.

[b] The differences for soybean, but not corn, between the two management systems were significantly different at the 5% level of significance.

A study of 51 experimental sites for peanut production in Florida, Mississippi, Georgia, and Alabama indicated application of FGD gypsum increased income at 36 of the sites (Figure 5-1 and Table 5-2). A study in Mississippi (Sumner and Larrimore, 2006) indicated that application of gypsum at 2 tons per acre significantly increased tomato yield and value (Table 5-3). Similar studies for horticultural crops in Ohio have not been conducted.

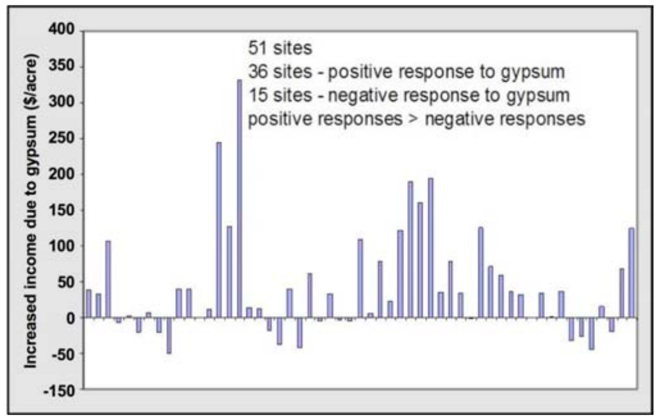

Figure 5-1. Income response for application of FGD gypsum for peanut in the southeastern United States. (Sumner, 2007.)

Table 5-2. Effect of FGD Gypsum on Peanut Yields and Value in Florida, Mississippi, Georgia, and Alabama. (Sumner and Larrimore, 2006.)

State	Rate of Gypsum	Yield	Value
	tons/acre	lbs/acre	$/acre
Florida	0	3,280	540
	0.5	3,940	649
Mississippi	0	2,940	503
	0.5	3,260	564
Georgia	0	813	112
	1.0	1,210	185
	2.0	1,290	198
Alabama	0	4,100	754
	0.5	5,410	995

Table 5-3. Effect of Gypsum on Tomato Yield and Value in Mississippi.

Gypsum	Yield	Value
tons/acre	lbs/acre	$/acre
0	14,800	5,900
2	17,700	7,070

Application of gypsum to ameliorate acid subsoil may increase the yield and value of crops not only in the application year but even more so in the following years. One example was increased yield and value of cotton several years after a single application. The result was a much greater cumulative profit where gypsum was applied than where it was not used (Table 5-4). It must be noted that after the first year, the economic return was actually negative. Also, correction of subsoil acidity or improved soil aeration and water infiltration are benefits that may not be immediately noticed. The benefits of gypsum must be substantial enough, over multiple years, to justify the cost of application. The producer will then be more likely convinced that the long-term benefits will eventually repay the costs involved for purchase, transportation, and spreading.

Table 5-4. Effect of Gypsum on Cotton Yield and Cumulative Profit in Georgia. (Sumner, 2007.)

Treatment	Lint Cotton Yield (lbs/acre)				
	2000	2001	2002	2003	2004
Control	310	770	892	339	665
Gypsum	309	989	1,117	384	774
Difference	–1	219	225	45	109
Value ($)	0	109	112	22	54
Cumulative profit ($)	–50	59	171	193	247

Some of the previous examples are for application of mined gypsum, but FGD gypsum represents a new source that is increasingly becoming available. Research conducted to date shows that FGD gypsum for agricultural uses performs similarly in comparison to other products that are routinely used for the same purposes. Thus, if the combined costs of purchasing, transport, and spreading are similar or lower for FGD gypsum, its use would seem to be warranted.

Electricity-producing utilities that rely on coal as an energy source are a major source of FGD gypsum. Currently, most FGD gypsum is produced in the eastern United States. Transportation costs are a major impediment to many agricultural uses of FGD gypsum. Potential markets located in the western United States may never become economically viable for FGD gypsum produced in the eastern United States unless FGD gypsum producers are located on navigational rivers or along rail lines. Barges offer an attractive way of moving materials and can be linked to rail or truck transportation to move material. Generalized shipping rates (cents per ton-mile) are 0.97 for barge, 2.53 for rail, and 5.35 for truck transport. Most growers will be reluctant to pay more than $20–25 per ton for FGD gypsum delivered and spread on their fields.

To reduce transportation costs, the FGD gypsum must be dewatered. This can be done by simply placing the FGD gypsum in piles and allowing gravity to leach the water out of the piles. A dedicated dewatering facility may also be used to reduce the water content in FGD gypsum. Cost of constructing a dewatering facility ranges from $3 to $6 million (Miller, 2006). Costs are about $3 per ton to operate a dewatering facility. Thus it is doubtful that mechanical dewatering can be justified based solely on an agricultural market. At sites where FGD gypsum must be mechanically dewatered so that it can be hauled to a stacking area for disposal, the utility will not avoid the dewatering costs but could still provide gypsum for agriculture in the immediate area of where it is produced. Cost of hauling varies but the rule of thumb for estimating trucking costs is $1 per ton to load a truck, $1 per ton for the first mile, and $0.10 per ton for each additional mile hauled.

For end users, ordinary spreaders for application of fertilizers may be used for FGD gypsum application. Many farm cooperatives or growers already have this equipment for fertilizer applications and do not need to purchase anything new for application of the FGD gypsum. The cost for a new spreader at the present time (2010) can approach $100,000. Truck loading equipment, or some other means of loading, will also be required. However, ordinary loading equipment is often a necessary tool on most farms so that purchase of a loader specifically to handle FGD gypsum would not be necessary. The spreading costs for FGD gypsum would be similar to spreading costs for lime.

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Analytical and Technical Support

Sampling and Analysis of FGD Gypsum and Soil

A. Sampling FGD Gypsum for Analysis

To make the most appropriate and environmentally responsible use of new FGD gypsum sources, it is necessary to test the FGD gypsum to accurately determine the concentrations of its nutrients, calcium and sulfur. If there is concern about its environmental impact, concentrations of other elements such as arsenic, cadmium, lead, mercury, and selenium should also be measured. For the test results to be meaningful, it is important to obtain an adequate number of samples that are representative of the stockpile of FGD gypsum. The number of samples needed depends on the variability of FGD gypsum. The more variable the FGD gypsum, the more samples are required. FGD gypsum from different storage systems should be sampled separately. The composition and concentrations of elements of environmental concern in FGD gypsum depend on the type of coal, scrubbing process, and sorbent used in the desulfurization process.

FGD gypsum subsamples should be collected from at least three representative locations in stockpiled gypsum and at least 20 inches below the surface. At each spot, a minimum of one pound of FGD gypsum should be collected and put in a plastic bag. Total weight of the sample will be about 3–5 pounds. Identify the sample container with information regarding its source and a date. After packaging, FGD gypsum samples may be sent to the STAR Laboratory (**http://www.oardc.ohio-state.edu/starlab/**) at the Ohio Agricultural Research and Development Center in Wooster, Ohio, for chemical analysis.

FGD samples from five power plants in Alabama, Arkansas, Indiana, North Dakota, and Ohio were collected and sent to the Ohio Agricultural Research and Development Center for relevant agronomic analysis. The results are provided in Table 6-1. It is evident that FGD gypsum is an excellent source of calcium and sulfur for supporting crop growth.

B. Sampling Soil for Analysis

To obtain a representative soil sample, subsamples must be collected from at least three spots in each uniform field area from the surface to 20 cm depth. Approximately one-half pound of soil at each spot is collected and put in a plastic bag. Total weight of a sample is about two pounds. Identify the sample container with information regarding the field and date. After packaging, soil samples may be sent to the STAR Laboratory (**http://www.oardc.ohio-state.edu/starlab/**) at the Ohio Agricultural Research and Development Center in Wooster, Ohio, or a commercial laboratory of choice for chemical analysis. For more information about soil sampling and analysis, see the *Ohio Agronomy Guide* (Ohio State University Extension, 1995). The use of this data for making gypsum rate recommendations is provided in Chapter 4.

Table 6-1. Chemical Characteristics of FGD Gypsum from Five States. (FGD Gypsum Agricultural Network, 2008.)

Parameter	State 1	State 2	State 3	State 4	State 5
pH	7.7	8.4	8.0	7.7	7.7
EC† (dS/m)	1.8	3.8	2.0	1.9	2.0
TNP† (%)	10	< 5.0	13	21	3.2
Calcium (mg/g)	203	202	192	200	88
Sulfur (mg/g)	157	174	178	183	184

† EC is electrical conductivity and TNP is total neutralization potential.

Institutional Support

Ohio State University Extension

The primary objective of The Ohio State University and Ohio State University Extension (OSU Extension) is to provide Ohio's citizens with objective research-based information (**http://www.extension.osu.edu**). OSU Extension provides a wide range of research-based educational programs and publications. Information is available through professional Extension educators in each county and through state specialists. Publications such as fact sheets and bulletins can also be downloaded from the Ohioline website (**http://ohioline.osu.edu/**). The Ohioline website is maintained by the College of Food, Agricultural, and Environmental Sciences of The Ohio State University. This site is used extensively by the citizens of Ohio to obtain credible information related to agricultural and environmental issues. An Extension fact sheet entitled *Gypsum for Agricultural Use in Ohio—Sources and Quality of Available Products* can be downloaded from the Ohioline site.

National Research and Demonstration Network of FGD Products in Agriculture

A complementary project to this one is the National Research and Demonstration Network of FGD Products in Agriculture (**http://www.oardc.ohio-state.edu/agriculturalfgdnetwork/**). Research has been completed or is currently being conducted in Alabama, Arkansas, Indiana, New Mexico, North Dakota, Ohio, and Wisconsin.

Members of the national network have organized three workshops about land application uses of FGD products. These workshops were held in St. Louis (2006), Atlanta (2007), and Indianapolis (2009). Papers presented in the workshops can be accessed at the FGD Network website (**http://www.oardc.ohio-state.edu/agriculturalfgdnetwork/**).

American Coal Ash Association (ACAA)

The mission of the American Coal Ash Association (ACAA) is to advance the management and use of coal combustion products in ways that are environmentally responsible, technically sound, commercially competitive, and more supportive of a sustainable global community. The association accomplishes its mission through public-private partnerships, technical assistance, education, publications, meetings, workshops, and other activities and initiatives. The ACAA facilitates connections among members as well as diverse entities and interests to stimulate proper use of gypsum. Additional information can be obtained at **http://acaa.affiniscape.com/index.cfm**.

Soil and Crop Consultants

Soil and crop consultants are qualified individuals who offer planning and technical assistance to agricultural producers and make natural resource management decisions. Producers are not required to use private consultants, but they have this option for help with FGD gypsum management. Several soil and crop consultants have experience working with FGD gypsum uses in agriculture. You may find more information by conducting a web search using the search terms of "FGD gypsum" and "agriculture."

Rules and Regulations

Rules and regulations concerning FGD gypsum use in agriculture and information about those rules are constantly being revised. It is important to verify the regulatory status of FGD gypsum and any requirements for its use with the appropriate state's environmental agency.

The principal federal law that regulates hazardous and solid wastes is the Resource Conservation and Recovery Act (RCRA). Subtitle C of RCRA regulates wastes that are both "solid" and "hazardous." Wastes that are not considered hazardous are regulated under Subtitle D, which passes landfill permitting and monitoring responsibilities to the states. In 1980, RCRA was amended by adding what is known as the Bevill exclusion, to exclude "solid waste from the extraction, benefication, and processing of ores and minerals" from regulation as hazardous waste under Subtitle C of RCRA. This exclusion holds until a determination is made by the EPA Administrator either to promulgate regulations under Subtitle C or to declare such regulations unwarranted.

As required by Congress, the U.S. Environmental Protection Agency (U.S. EPA) published regulatory determinations in 1993 for fly ash, bottom ash, boiler slag, and FGD materials and in 2000 for fluidized bed combustion wastes, co-managed wastes, and wastes from coal combustion by non-utilities, petroleum coke combustion, co-burning of coal and fuel, and oil and natural gas combustion. These determinations concluded that regulation of CCPs under Subtitle C was not warranted and that federal regulation of beneficial use was not necessary. However, it was concluded that national regulations for disposal in landfills and surface impoundments under Subtitle D should be developed. In addition, the EPA indicated it would continue to review information related to coal combustion by-products.

As a result of the regulatory determination made in 1993 and 2000, states have developed their own regulatory systems for CCBs. All states except California, Washington, Rhode Island, and Tennessee designate FGD materials as exempt from regulation as hazardous wastes (Table 6-2). Those four states treat FGD materials like all other industrial wastes and require FGD material to be tested to determine if they contain constituents at levels used to define hazardous wastes. If these levels are exceeded, the material is treated as a hazardous waste. If not, the materials are treated as a non-hazardous waste. Most states regulate FGD materials as solid wastes and some categorize it more narrowly as industrial solid wastes, or special wastes. New Jersey, Oklahoma, and Utah exempt coal combustion by-products as solid wastes under certain uses or conditions.

Table 6-2. State Regulations for FGD Gypsum.

Regulation	State
Chemical analysis before being exempted as hazardous waste	California, Rhode Island, Tennessee, Washington
Land application as solid waste	Illinois, Maryland, Michigan, Missouri, Nebraska, North Carolina, Pennsylvania, Virginia, West Virginia
No law or as solid waste case-by-case	Alabama, Alaska, Arizona, Arkansas, Colorado, Connecticut, Delaware, Georgia, Hawaii, Idaho, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Massachusetts, Minnesota, Mississippi, Missouri, Montana, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Dakota, Ohio, Oklahoma, Oregon, South Carolina, South Dakota, Texas, Utah, Vermont, Wisconsin, Wyoming

States that currently have laws authorizing land-application uses are Illinois, Maryland, Michigan, Missouri, Nebraska, North Carolina, Pennsylvania, Virginia, and West Virginia. The specific language describing reuse varies by state but is generally defined for materials being used as a soil substitute, additive or nutrient additive, conditioner, or amendment. Illinois, Maryland, Pennsylvania, and Virginia include mine reclamation as a reuse. Virginia appears to have one of the broadest definitions for reuse as a soil nutrient or other agricultural use. Maryland includes reuse as a soil improver or conditioner.

Thirty-two states do not have laws or permit-by-rule arrangements specifically authorizing reuse of FGD materials. Several states (Indiana, New York, Texas, Utah, and Wisconsin) that have laws authorizing reuse of FGD materials generally specify construction (road building) or other engineering uses instead of land-application uses. Fifteen states evaluate proposals for reuse on a case-by-case basis. Ohio and Oklahoma lack specific laws for reuse but do permit land application under other administrative arrangements.

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CHAPTER 7

Gypsum Handling and Storage

In this chapter, we briefly provide information about gypsum handling and storage, with special attention paid to FGD gypsum.

Handling and Transportation

Gypsum, including FGD gypsum, is not combustible or explosive. FGD gypsum is also not expected to produce any unusual hazards during normal use. Under ordinary conditions, no glasses or goggles, gloves and protecting clothing, and respiratory protection are required for handling of FGD gypsum. However, exposure to high dust levels may irritate the skin, eyes, nose, throat, or upper respiratory tract. Therefore, as much as possible, minimize dust generation and accumulation and avoid breathing FGD gypsum dust. In storage areas, provide ventilation sufficient to control airborne dust levels. If dust is being generated, wear the appropriate eye protection, such as safety glasses or goggles, and a dust respirator (Figure 7-1).

Figure 7-1. Goggles and mask for eye and respiratory protection.

FGD gypsum can build up or adhere to the walls of a confined space, and the FGD gypsum can release, collapse, or fall unexpectedly. To prevent burial or suffocation, do not enter a confined space, such as a silo, bin, bulk truck, or other storage container or vessel that stores or contains FGD gypsum.

FGD gypsum is not classified or regulated. It is not like hazardous materials that require Department of Transportation shipping permission and documentation for transportation. Depending on the distance from the FGD gypsum source to locations where FGD gypsum is used, trucks, rail cars, and river barges may be used for FGD gypsum transportation (Figure 7-2). Currently, the most common way to transport FGD gypsum is by truck.

Figure 7-2. Trucks (left), rail cars (middle), and river barges (right) are used for FGD gypsum transportation. (From FGD Network website: http://www.oardc.ohio-state.edu/agriculturalfgdnetwork.)

The issue of transportation costs understandably arises whenever potentially large volume uses of FGD gypsum are proposed. Comparative generalized shipping rates (cents per ton-mile) are lowest for barge, intermediate for rail, and highest for truck transport. Some rules of thumb that pertain to FGD transport is that it can be transported up to 551 miles by barge, 211 miles by rail, but only 100 miles by truck before the shipping costs exceed its value. If the source and markets for the material are near a navigable waterway or rail line, and assuming a 100-mile radius is the truck transportation limit, material storage sites located at 200-mile intervals along a rail line or barge route could be set up for moving the FGD gypsum from the utility to the farmer.

Gypsum Storage

FGD gypsum may be stored in the open or in a covered structure (Figure 7-3). FGD gypsum storage should accomplish the following goals: (1) Minimize water interaction; (2) reduce dust; (3) balance capital investment, cash flow requirements, and labor costs, and (4) maintain good physical condition of the FGD gypsum for spreading. FGD gypsum storage is needed to provide handling and spreading flexibility. Spreading is often seasonal and needs to be scheduled to avoid wet ground, poor weather conditions, growing crops, and conditions conducive to causing pollution.

Storage areas or facilities should be constructed to minimize any potential dust, surface water runoff problems, and access by animals through proper fencing. Although higher in cost, a covered structure may be practical due to improved handling conditions, less or no surface water runoff, and less spreading of dust. Dewatered gypsum stored in a roofed storage shed without side walls may need a wind screen to prevent dusting. FGD gypsum stored outside will generally form a crust that helps shed water and prevents dusting so long as it is undisturbed. If the crust is broken, a dusting problem may result.

Figure 7-3. Gypsum stockpiled in the field for post-harvest application (left), in the coal-fired power plant for marketing (middle), and in the covered structure (right). (From the FGD Network website: http://www.oardc.ohio-state.edu/agriculturalfgdnetwork.)

When planning the construction of FGD gypsum storage facilities, things to consider include building locations, well locations, future building expansions, and prevailing winds. The storage facility will also need to be properly sized for convenient filling and emptying. As much as possible, all-weather access should be provided. Both open and in facility FGD gypsum storage systems have advantages and disadvantages. A detailed comparison is provided in Table 7-1.

Table 7-1. Comparison of FGD Gypsum Storage Alternatives.

FGD Storage Type	Advantages	Disadvantages
Open (not covered)	Inexpensive.	Rainfall adds extra water. Rainfall/runoff contamination potential. Runoff controls may be required.
Open (covered with plastics)	Less expensive. No rainfall effects. Maintains FGD gypsum moisture.	Not feasible for long-term storage.
Open sided (roof cover only)	No rainfall effects. Maintains FGD gypsum moisture.	Expensive.
In facility	No rainfall effects. Feasible for long-term storage. Maintains FGD gypsum moisture.	Most expensive.

Water runoff from FGD gypsum stockpiles, whether from rainfall or snowmelt, may contain unaltered FGD gypsum and soil. If gypsum is stockpiled in an individual field for post-harvest application and then completely spread before winter, no action is needed other than that of constructing a temporary storage pile. If gypsum is stored in large piles in an open-lot system, a management plan should be developed to avoid dust and water problems from developing and to restrict cattle access. Runoff can be collected and transferred to a settling basin or holding pond by constructing diversion, curbs, gutters, lot paving, and, in some cases, by pumping (Figure 7-4). A settling basin or a holding pond retains runoff and reduces the flow rate to allow settling out and recovery of FGD gypsum. Typically, any runoff FGD gypsum that will settle out will do so in about 30 minutes. To prevent scouring of the settled FGD gypsum from the settling basin, the liquid cross-sectional area that enters the pond should be about 5% of the ponded surface area. After settling, the liquids can be drained off to a constructed wetland or vegetative treatment area, used for irrigation, or discharged to a surface water body.

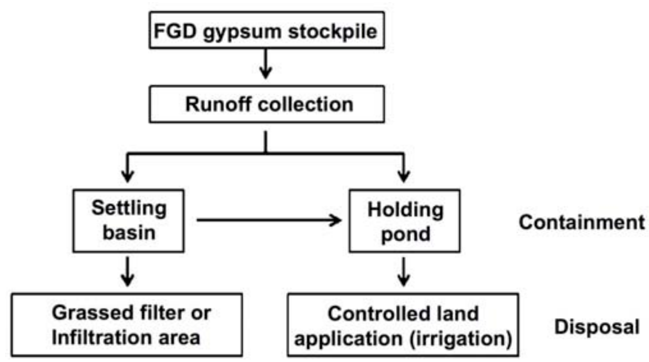

Figure 7-4. Components of a runoff control system.

When FGD gypsum is stored, dust control is important. Moisture content and weather conditions significantly affect dust generation and transportation. Dust is generated from FGD gypsum storage and handling systems. FGD gypsum that has moisture content as low as 5% will not cause dust problems while loading. However, dry FGD gypsum that has moisture content less than 5% will dust while being spread using a spinner spreader, especially on windy days (Figure 7-5). Application can also be done using a drop box spreader, which helps control potential dusting problems.

Figure 7-5. Application on dry windy days may generate dust. (Curtis, 2007.)

For FGD gypsum producers, using covered conveyors at transfer points is one of the best ways for dust control when distributing FGD gypsum to marketers or end users (Figure 7-6). However, this method is not necessary for most users to transfer their FGD gypsum to fields from the stockpile because of great capital investment and the difficulty of installation. Often, FGD gypsum that is stored uncovered outside will form a crust and prevent dusting. Treating FGD gypsum stockpiles by spraying water can also prevent dusting.

Figure 7-6. A covered conveyor distributes FGD gypsum at transfer points. (Miller, 2007.)

References

Curtis, K. 2007. Marketing of FGD gypsum in the Midwest United States. Presented at the workshop on Agricultural and Industrial Uses of FGD Gypsum. October 2007 in Atlanta, Ga. http://library.acaa-usa.org/2-Marketing_of_FGD_Gypsum_in_the_Midwest_US.pdf.

Miller, E. C. 2007. What is FGD gypsum? Presented at the workshop on Agricultural and Industrial Uses of FGD Gypsum. October 2007 in Atlanta, Ga. http://library.acaa-usa.org/2-what_is_FGD_Gypsum.pdf.

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Abbreviations and Basic Conversion Factors

CCP — Coal combustion product

CEC — Cation exchange capacity

EC — Electrical conductivity

FGD — Flue gas desulfurization

GR — Gypsum requirement

TNP — Total neutralization potential

ppm (parts per million) — mg/kg

ppb (parts per billion) — µg/kg

ppt (parts per trillion) — ng/kg

Element Symbols

Element	Symbol	Element	Symbol	Element	Symbol
Aluminum	Al	Copper	Cu	Phosphorus	P
Antimony	Sb	Iron	Fe	Potassium	K
Arsenic	As	Lead	Pb	Sodium	Na
Barium	Ba	Lithium	Li	Sulfur	S
Beryllium	Be	Magnesium	Mg	Selenium	Se
Boron	B	Manganese	Mn	Silicon	Si
Cadmium	Cd	Mercury	Hg	Strontium	Sr
Calcium	Ca	Molybdenum	Mo	Thallium	Tl
Chromium	Cr	Nickel	Ni	Vanadium	V
Cobalt	Co	Nitrogen	N	Zinc	Zn

Conversion Factors for SI and Non-SI units

To convert Column 1 into Column 2, multiply by	Column 1 SI Unit	Column 2 Non-SI Unit	To convert Column 2 into Column 1, multiply by
Area			
2.47	Hectare, ha	Acre	0.405
247	Square kilometer, km^2 (106 m^2)	Acre	4.05×10^{-3}
0.386	Square kilometer, km^2 (106 m^2)	Square mile, mi^2	2.590
2.47×10^{-4}	Square meter, m^2	Acre	4.05×10^{3}
10.76	Square meter, m^2	Square foot, ft^2	0.0929
1.55×10^{-3}	Square millimeter, mm^2 (10-6 m^2)	Square inch, in^2	645
Volume			
9.73×10^{-3}	Cubic meter, m^3	Acre-inch	102.8
35.3	Cubic meter, m^3	Cubic foot, ft^3	0.0283
6.10×10^{4}	Cubic meter, m^3	Cubic inch, in^3	1.64×10^{-5}
0.0284	Liter, L (10^{-3} m^3)	Bushel, bu	35.24
1.057	Liter, L (10^{-3} m^3)	Quart (liquid), qt	0.946
0.0353	Liter, L (10^{-3} m^3)	Cubic foot, ft^3	28.3
0.265	Liter, L (10^{-3} m^3)	Gallon	3.78
33.78	Liter, L (10^{-3} m^3)	Ounce (fluid), oz	0.0296
2.11	Liter, L (10^{-3} m^3)	Pint (fluid), pt	0.473
Mass			
2.20×10^{-3}	Gram, g (10^{-3} kg)	Pound, lb	454
0.0352	Gram, g (10^{-3} kg)	Ounce, oz	28.4
2.205	Kilogram, kg	Pound, lb	0.454
0.01	Kilogram, kg	Quintal (metric), q	100
1.10×10^{-3}	Kilogram, kg	Ton (2000 lb), ton	907
1.102	Megagram, Mg (tonne)	Ton (U.S.), ton	0.907
1.102	Tonne, t	Ton (U.S.), ton	0.907
Yield and Rate			
0.893	Kilogram per hectare, kg ha^{-1}	Pound per acre, lb $acre^{-1}$	1.12
0.0777	Kilogram per cubic meter, kg m^{-3}	Pound per bushel, lb bu^{-1}	12.87
0.0149	Kilogram per hectare, kg ha^{-1}	Bushel per acre, 60 lb	67.19
0.0159	Kilogram per hectare, kg ha^{-1}	Bushel per acre, 56 lb	62.71
0.0186	Kilogram per hectare, kg ha^{-1}	Bushel per acre, 48 lb	53.75
0.107	Liter per hectare, L ha^{-1}	Gallon per acre	9.35
893	Tonnes per hectare, t ha^{-1}	Pound per acre, lb $acre^{-1}$	1.12×10^{-3}
893	Megagram per hectare, Mg ha^{-1}	Pound per acre, lb $acre^{-1}$	1.12×10^{-3}
0.446	Megagram per hectare, Mg ha^{-1}	Ton (2,000 lb) per acre, ton acre	2.24

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