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PHOSPHOGYPSUM USES IN AGRICULTURE

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ABSTRACT

Phosphogypsum ($CaSO_4$), a by-product of phosphoric acid production from rock phosphate is a potential source of calcium and sulfur for plants, as well as an ameliorant for alkaline and sodic soils. Phosphogypsum production worldwide exceeds 150 million Mg annually, with only about 4 percent being used in agriculture and industry and the rest being dumped into the ocean or stock piled as a waste. Florida leads in the production of phosphogypsum in the United States with an annual production of 33 million Mg and about 600 million Mg in stacks, and a projection of 1 billion Mg by the year 2000. This paper will discuss the various agronomic uses of phosphogypsum (i.e. source of nutrients for plants, conditioner for sodic soils, hard-setting clay soils and subsoil hardpans, and the acidifying benefits on high pH soils to help alleviate micronutrient deficiencies). This paper will also discuss any potential environmental hazards to be concerned with from using phosphogypsum in agriculture.

INTRODUCTION

Gypsum ($CaSO_4xH_2O$) is available for agricultural use either as mined gypsum or as a chemical byproduct. Gypsum byproducts are produced in phosphoric, hydrofluoric, and citric acid production and in pollution control systems, such as in the neutralization of waste sulfuric acid and in flue-gas desulfurization. Phosphogypsum is the term used for the gypsum byproduct of wet-acid production of phosphoric acid from rock phosphate. It is essentially hydrated $CaSO_4$ with small proportions of P, F, Si, Fe, Al, several plant micronutrients, heavy metals, and radionucleides as impurities. Among the gypsum byproducts, only phosphogypsum is of worldwide importance in quantity and distribution.

Rock phosphate deposits are found throughout the world, and on these deposits the phosphoric acid industries are built. Countries with no natural phosphate deposits import the rock to produce phosphoric acid for their industry and agriculture. Therefore, the production of byproduct phosphogypsum is more widely distributed around the world than the natural deposits of rock phosphate. In fact there are over 150 million Mg of phosphogypsum accumulating annually worldwide, most of which is stacked in piles as waste material.

Byproduct phosphogypsum has a wide variety of uses throughout the world. Such uses include using phosphogypsum for road bed and embankment materials, wall board production, concrete production, animal feed supplement, soil amendment, and use as a fertilizer. This paper will concentrate on the advantages of using phosphogypsum in crop production.

IMPORTANCE OF SULFUR FOR CROP PRODUCTION

Sulfur is one of the essential nutrients required for crop production. In general, plants contain as much S as P, the usual range being from 0.2 to 0.5% on a dry-weight basis. Sulfur ranks in importance with N as a constituent of the amino acids cysteine, cystine, and methionine in proteins that account for 90% of S in plants. It is also involved in the formation of oil in crops such as peanut (Arachis hypogaea L.), soybean (Glycine max (L.) Merr.), flax (Linum usitissimum), and rapeseed (Brassica campestries).

In the past three decades, S deficiencies have been reported with increasing frequency throughout the world. The reasons given for the increasing S deficiencies worldwide are (a) the shift from low-analysis to high-analysis fertilizers containing little or no S, (b) use of high-yielding crop varieties that remove greater amounts of S from the soil, (c) reduced industrial S emission into the atmosphere due to pollution-control measures and decreased use of high-S fossil fuels, (d) decreased use of S in pesticides, and (e) declining S reserves in soil due to erosion, leaching, and crop removal. Increased consumption of S-free, high-analysis fertilizers is seen as the most important reason for the increasing S deficiency worldwide.

IMPORTANCE OF CALCIUM IN CROP PRODUCTION

Calcium with concentration ranging from 0.2 to 1.0% in plant tissue, is also essential to plant life. Calcium deficiency manifests itself in the failure of terminal buds and apical tips of roots to develop. Also, lack of Ca results in general breakdown of membrane structures, with resultant loss in retention of cellular diffusible compounds. Disorders in the storage tissues of fruits and vegetables frequently indicate Ca deficiency.

The need for Ca by plants may be readily supplied by liming materials such as calcitic and dolomitic limestone. However, lime application in large amounts on certain soils could be detrimental to plant growth. Kamprath (1971), in a review of the effect of lime on Oxisols and Ultisols, reported that lime application that raised the soil pH to 7 resulted in reduced rate of water infiltration, reduced availability of P, B, Mn, and Zn, and reduced growth of sudangrass (Sorghum vulgare var. sudanse L.), corn (Zea mays L.) and soybean. Therefore, for certain soils that need amelioration using large amounts of Ca to support commercially variable cropyields, or for crops that need large amount of readily soluble source of Ca such as peanut, a source other than lime may be necessary.

Thus, with increasing S deficiencies worldwide and the need for a Ca source other than the liming materials, phosphogypsum deserves serious consideration for agricultural applications that traditionally use mined gypsum.

CEREAL CROPS

It has been well documented that cereal crops will respond to S application when grown on soils deficient in S. Crops grown on soils which are low in organic matter, fine loamy to coarse textured, moderately - well to well drained soils with extractable soil - S of less than 7 kg SO_4-S ha^{-1} in the surface horizon tend to respond well to sulfur addition.

Studies conducted in Florida, U.S.A. have shown the addition of 1.7 to 2.2 Mg phosphogypsum ha^{-1} to increase green corn yields by as much as 107%. Other studies conducted in North Carolina, U.S.A. have shown corn response to gypsum application to be dependent upon the rate of N. At 56 or 112 kg N ha^{-1} gypsum had no effect on corn yield or N content of grain.

Studies conducted by the International Fertilizer Development Center in Togo, West Africa have also demonstrated phosphogypsum addition (10 to 50 kg S ha^{-1}) to increase corn grain yields by 44 to 77% over control plots. Similar results have also been obtained in Iraq.

Oates and Kamprath (1985) found that gypsum was as effective as ammonium sulfate as a source of S for winter wheat (Triticum aestivum L.). Plants responded to gypsum at rates from 22 to 90 kg S ha^{-1} where nonfertilized plants had S concentrations of 0.6 g kg^{-1} of dry matter and an N:S ratio of 21:1. Baird and Kamprath (1980) suggested that improved efficiency of S uptake by winter wheat from applied gypsum should occur on sandy soils by applying gypsum as a topdressing in early spring. In Bangladesh, Mazid (1986) reported that wheat yields from 1042 fertilization trials increased by an average of 21% due to gypsum applied at the rate of 20 kg S ha^{-1}.

Results from demonstration trials on the effect of 124 kg gypsum (16% S) ha^{-1} on rice (Oryza sativa L.) in Bangladesh showed that 97% of 3,368 demonstration sites responded to gypsum (Mazid, 1986). Rice yields in gypsum-treated sites increased 19 to 41% over that of the recommended NPK-fertilized plots without gypsum. Crop responses to gypsum occurred mainly in calcareous and continuously submerged soils and were more profitable in the monsoon season than in the dry season. Studies in Indonesia found that ammonium sulfate, potassium sulfate, elemental S, and gypsum were equally effective as a source of S for rice (Momuat et al., 1983). Chien et al. (1987), in a greenhouse study, demonstrated that response of rice to gypsum was not dependent on the method of application. Sulfur uptake and grain yield were not different whether gypsum was broadcast, incorporated, or placed deep into the soil.

GRAIN LEGUMES

Peanuts possess a unique nutritional habit in that supplemental Ca must be applied to the "peg", a modified stem that penetrates the soil surface to form the pod or nut. Numerous experiments have shown that supplemental Ca applied at flowering improved yield and quality of large-seeded peanuts. The role of Ca in reducing pod rot incidence in peanut is also well known. Walker and Csinos (1980) demonstrated that increasing rates of gypsum from 0.56 to 1.68 Mg ha^{-1} resulted in corresponding reduction in pod rot in five peanut cultivars.

As early as 1945, Colwell and Brady (1945) have established the superiority of gypsum over limestone in supplying the Ca requirements of peanut. Since then, the peanut-producing belt of the southeastern United States has used fine-ground (anhydride) mined gypsum, as the principal Ca source for peanut, broadcast at a rate of 0.5 to 1.0 mg ha^{-1} at first flowering when Mehlich I extractable soil Ca is <560 kg ha^{-1}.

Sullivan et al. (1974) showed that application of dolomitic limestone on peanut, based on soil test, increased soil pH and soil Ca levels but did not improve seed quality and yield. On the other hand, gypsum at 0.673 Mg ha^{-1} reduced soil pH and the detrimental effects of K on fruit yield and quality, improved seed germination, seedling survival and vigor, and increased yield and improved seed quality. Daughtry and Cox (1974) found that three commercial gypsum materials, namely; fine-ground and granular anhydride gypsum and phosphogypsum supplied at the rate of 0.76 Mg $CaSO_4$ ha^{-1} at flowering, produced no difference in the yield of Florigiant peanut. Hallock and Allison (1980) used similar commercially-formulated fine-ground (Bagged LP) and granulated (420 LP Bulk) anhydride gypsum, and granulated phosphogypsum (Tg Gypsum) as source of Ca for Virginia-type peanuts at the rate of 0.605 Mg ha^{-1}. After two years of testing (1977 and 1978), the results indicated that, in general, granulated phosphogypsum and mined gypsum were as effective as fine-ground gypsum for supplemental Ca for peanuts. When fruit matured under very dry conditions, granulated phosphogypsum and fine-ground mined gypsum were superior over granulated mined gypsum. Gascho and Alva (1990), used seven gypsum materials including phosphogypsum as a source of Ca for Florunner peanuts. They concluded that no other source of gypsum exceeded phosphogypsum in solubility, or in its beneficial effects on peanut grade and yield when broadcast at the rate of 224 kg Ca ha^{-1} at first bloom.

In Brazil, Vitti et al. (1986) reported that application of 0.1 Mg ha^{-1} of phosphogypsum to soybean on an Oxisol increased grain yield by as much as 43% and in Ultisol by 37%. At 0.25 Mg ha^{-1}, phosphogypsum increased grain yield of beans (Phaseolus vulgaris L.) by 13% in Ultisol and 54% in Oxisol soil. Phosphogypsum rates used were very low so that the positive responses of the crops could be attributed more to S or Ca as nutrients than to the ameliorative effect of phosphogypsum on subsoil acidity.

SUGARCANE

Golden (1983) reported that the application of phosphogypsum at 2.24 Mg ha^{-1} to sugarcane (Saccharum officinarum L.) in Louisiana increased stubble cane yield. Breithaupt (1989), using both phosphogypsum and fluorogypsum on sugarcane at rates of 2.24 to 22.40 Mg ha^{-1}, reported significant increases in cane and sugar yields in treated plots over the control in both plant cane and first year stubble harvests. Both gypsum byproducts were equally effective in increasing both cane and sugar yields.

FRUITS AND VEGETABLES

In Florida, phosphogypsum up to 2.24 Mg ha^{-1} applied to different varieties of citrus (Citrus sinensis) increased juice brix and reduced juice titratable acidity. It did not, however, increase fruit yield (Myhre et al., 1990). In Brazil, pineapple [Ananas comosus (L.) Merill. cv. Smooth Cayene] fertilized with phosphogypsum in combination with KCl as a substitute for K_2SO_4. Potassium sulfate-fertilized fruits, however, had better fruit juice quality than those fertilized with KCl alone or in combination with phosphogypsum. Use of raw phosphogypsum at 1.68 and 2.24 Mg ha^{-1} on various vegetable crops in 1986 in Florida increased the yields of tomatoes (Lycopersicon esculentum Mill) by 6%, potatoes (Solanum tuberosum L.) by 19%, and watermelons (Citrullus vulgaris) by 49%. Residuals from phosphogypsum applied in 1986 at 2.24 Mg ha^{-1} also increased the yields of potatoes by 22% and cantaloupes (Cucumis melo) by 42% with more number of fruits weighing 1.0 kg or more each. Pelleted phosphogypsum supplied to the 1987 crop did not increase the yields of potato and bell pepper (Capsicum annuum). The phosphogypsum pellets remained intact but soft, indicating only partial dissolution.

FORAGE CROPS

Thomas et al. (1951) demonstrated conclusively that S deficiency limits non-protein N utilization in purified diets for ruminants, and that SO_4-S as sole source of S can correct the deficiency. Hume and Bird (1970) had shown that an intake of 1.9 g S per day by sheep produced the maximum protein production in the rumen microorganisms. Bray and Hemsley (1969) showed that S supplement to the diet increased bothcrude fiber digestion and S and N retention by sheep. Application of 86 kg S ha^{-1} using ammonium sulfate to bahiagrass (Paspalum notatum Flugge) increased dry matter yield by 25%, crude protein by 1.2%, and digestibility by 3 to 4% 30 days after application (Rechcigl et al., 1989). In a larger scale, studies in Ireland (Murphy et al., 1983) showed that cattle that grazed on S-fertilized pastures could gain up to 29% more weight than those grazing on S-deficient fields. Also, for any given daily liveweight gain, S-treated area had 21% more stock-carrying capacity the first year and 19% more the second year than the untreated pasture. These studies point not only to the need for S fertilization of forage crops for yield but also to the need to achieve a desirable range of N:S ratios to assure better feeding quality forage.

In plant protein, the N:S ratio is about 15:1 and remains fairly constant. If either S or N is limiting, protein synthesis is restricted, but the protein already synthesized will have a N:S ratio of about 15:1. Excess N relative to S supply accumulates as NO_3-N, amides, and amino acids. Excess S leads to SO_4-S accumulation (Stewart and Porter, 1969). Thus the wide variation in N:S ratios.

Sulfur fertilization of forage crops almost invariably results in reduced N:S ratio in plant tissue. Lancaster et al. (1971) reported that application of S at 40 mg kg^{-1} of soil in the form of Na_2SO_4 reduced N:S ratio from 32 to 9 for orchardgrass (Dactylis glomerata L.); 45 to 19 and 72 to 14 for first and second clippings, respectively, of sudangrass; 36 to 5 for ryegrass (Lolium multiflorum L.); 27 to 8 for alfalfa (Medicago sativa L.); and 33 to 16 for clover (Trifolium repens L.). On the other hand, in an 8-year field experiment using bermudagrass [Cynodon dactylon (L.) Pers], Woodhouse (1969) had shown that despite S fertilization excessive N application could produce a forage crop with N:S ratio in excess of 60:1.

In North Carolina, use of mined gypsum applied annually on coastal bermudagrass at the rates of 28 and 56 kg S ha^{-1} increased forage yields in 7 out of 8 years of data collection (Woodhouse, 1969). In Louisiana, Eichhorn et al. (1990) reported that annual application of 108 kg S ha^{-1}, using gypsum, increased bermudagrass yield by 16% over a 4-year period, with the highest increase (29%)

occurring in the fourth year. Digestible dry matter also increased by 14.5% over the same period. In Florida, Mitchell and Blue (1989) conducted a 6-year study to evaluate the effect of gypsum applied annually on Pensacola bahiagrass at 200 and 400 kg N ha^{-1}. They reported that a low N, gypsum application did not increase dry matter yield until the fourth year, with maximum yields thereafter predicted at an annual S application between 27 and 33 kg S ha^{-1}. At high N, 10 kg S ha^{-1} increased dry matter yield in the second year. By the fifth and sixth years, maximum dry matter yield was predicted at an annual rate of 40 to 51 kg S ha^{-1}. Results also showed that Sfertilization enhanced N recovery. Maximum relative forage yield was obtained at a concentration of 1.61 g S kg^{-1} dry matter. In a one-year study in Oklahoma, application of gypsum at the rate of 64 kg S ha^{-1} decreased N:S ratio of bermudagrass forage from 11.6:1 to 7.2:1 but did not increase yield, N uptake, or improve N efficiency (Westerman et al., 1983).

To date, very few studies have been conducted on the use of phosphogypsum on forage crops. Paulino and Malvolta (1989) used phosphogypsum on andropogon grass (Andropogon gayanus cv. Planaltina) grown in pot with soil taken from a Brazilian Cerrado site. Results showed that phosphogypsum, in the absence of lime, increased regrowth dry matter yield linearly up to the maximum rate of 120 kg S ha^{-1} used in the study. Maximum protein content was attained at 63 kg S or 380 kg phosphogypsum ha^{-1}. Lime had a significant negative effect on andropogon grass. Mullins and Mitchell (1990) used phosphogypsum as a source of S at the rates of 11 to 90 kg S ha^{-1} on wheat cut for forage in Alabama. Average increases in forage yield over a 3-year period ranged from 5.4 to 9.3% for two soil series. Comparison between mined gypsum and phosphogypsum showed no difference in forage yield of wheat. Phosphogypsum applied during fall or spring had no residual effect on yield of millet [Setaria italica (L.) Beauv] or sudangrass planted for summer forage after the winter wheat crop. In Florida, use of fresh phosphogypsum as a source of Ca applied at 2.24 to 4.48 ton ha^{-1} reduced soil pH and forage yield of ryegrass to levels below those of the control. Fresh phosphogypsum can be very acidic with pH a little over 2. A 3-year study (Rechcigl and Alcordo, 1992) evaluated phosphogypsum as a source of S and Ca for bahiagrass and ryegrass, without and with 1% dolomite or calcium carbonate needed to bring phosphogypsum pH (1:1) to 5.5. Annual rates of 0.2, 0.4, and 1.0 Mg ha^{-1} are compared to single phosphogypsum application rates of 2.0 and 4.0 Mg ha^{-1}. Results showed that phosphogypsum, with or without lime, increased the two-year total forage dry matter yields of bahiagrass by as much as 28% at 0.2 to 0.4 Mg phosphogypsum ha^{-1}. Phosphogypsum, across phosphogypsum rates, with dolomite gave the highest increase in dry matter yield with 12% over the control. Application of phosphogypsum or gypsum has been shown to deplete Mg at the surface horizon (Reeve and Sumner, 1972).

CROP RESPONSE TO GYPSUM AND PHOSPHOGYPSUM ON ACID SOILS

Failure of plant roots to grow into and proliferate at deeper soil horizons in acid soils, due to toxicity, limits their capacity to take up both plant nutrients and soil moisture. Highly weathered soils such as the Oxisols and Ultisols, whose mineralogy is normally dominated by 1:1 type clay and oxides and hydrous oxides of Al and Fe, not only retain very little moisture in the surface horizons after a rain, but also dry out very quickly during short periods ofrainless days. Wolf (1975) reported that in the Cerradoes of Central Brazil corn crops can wilt after only 6 days without rain even during the wet season.

Ritchey et al. (1980) reported that gypsum contained in ordinary superphosphate (OSP) increased subsoil pH, decreased Al saturation, and increased Ca and Mg status. Roots of corn plants fertilized with OSP reached to a depth of 120 cm, while those fertilized with triple superphosphate (TSP) reached a depth of only 45 cm and wilted after 2 weeks with no rain. Pavan et al. (1984), using undisturbed profiled of Oxisols, reported that application of gypsum reduced the level of exchangeable Al and increased Ca throughout the 100-cm profile depth. Improvements in yield over time as a result of gypsum paralleled its progressive movement into the subsoil with subsequent decreases in exchangeable Al (Hammel et al., 1985). Sumner et al. (1986), based on a four-year study on the effect of deep liming and surface application of gypsum on alfalfa, reported that gypsum at 10 Mg ha^{-1} mixed into the top soil increased dry matter yield of alfalfa by 25%. It reduced exchangeable Al and Al saturation and increased Ca throughout the 100-cm depth. Farina and Channon (1988) reported that surface-applied gypsum at 10 Mg ha^{-1} resulted in a cumulative grain yield of 3.4 Mg ha^{-1} after four cropping seasons. Progressive reduction in the level of exchangeable Al was accompanied by increased subsoil Ca, Mg, and SO_4-S. Water pH increased markedly in the zone of maximum SO_4-sorption/precipitation. Effects of gypsum on subsoil root development were striking by the fourth season. However this is contrary to the alfalfa studies of Rechcigl et al., (1987, 1988).

Studies on the use of phosphogypsum as an ameliorant for acid soils in Brazil were summarized by Shainberg et al. (1989) and Alcordo and Rechcigl (1993). Rates ranging from 0.5 to 6.0 Mg ha^{-1} of phosphogypsum significantly increased the yields of apples (Malus domestica), beans (Phaseolus vulgaris, coffee (Avabsica L.), rice, wheat, and corn. Sumner et al. (1990), evaluated gypsum and phosphogypsum applied at 5 to 10 Mg ha^{-1} incorporated into the soil in several field experiments on a range of soils in southeastern United States. The results indicate that there were no differences between the two $CaSO_4$ sources based on crop responses and soil reactions. Highly significant and economically profitable yield responses were obtained for alfalfa, corn, soybean, cotton (Gossypium hirsutum L.), and peaches (Prunus persica L.). Gypsum and phosphogypsum application enhanced root penetration and proliferation in the subsoil, where previous conditions often prevented root growth.

AMELIORANT FOR SODIC SOILS

CHARACTERISTICS OF SPODIC SOILS

In regions of the world where evapotranspiration exceeds rainfall, basic salts and carbonates move upward in the soil profile from the water table instead of downward as occurs in regions of acid soils. Rain water with its dissolved salts adds to salt accumulation in the upper horizon. Irrigation, while often necessary for crop production under arid or semi-arid conditions, can contribute to the build-up of salts in these soils, especially when the quality of irrigation water is poor. Soils containing both soluble salts and exchangeable Na at levels which interfere with the growth of most crops are classified as saline or sodic soils.

The most characteristic physical property of sodic soils is that they are highly dispersive due to Na ions in the exchange complex of the coloidal fraction, particularly the silicate clays. When placed in water of low salt concentration, aggregates from these soils imbibe water until the soil deflocculates into individual soil particles (Russell, 1973). The dispersed soil particles move down the soil profile with the water clogging the macro and micro pores to such extents that they reduce or even completely stop water infiltration through the profile (McIntyre, 1958). Upon drying, hard crusts develop at the surface which make seedlings emergence difficult. Poor hydraulic conductivity and surface crusting are the two major problems that need to be ameliorated to improve sodic soils for crop production.

USE OF GYPSUM AND PHOSPHOGYPSUM ON SODIC SOILS

Historically, mined gypsum has been used world-wide to reclaim or ameliorate sodic soils because of its abundance and low cost. The process of reclamation or amelioration of sodic soils involves (1) the replacement of Na by Ca ions in the exchange complex and (2) leaching excess Na out of the root zone. The process requires (1) the maintenance of a desired exchangeable Na fraction in the exchange complex and (2) the supply of electrolytes of a desired composition and ionic strength to the solution phase without increasing its alkalinity. The process requires the dissolution of gypsum, solute and water movement, and exchange of Na in the exchange complex with Ca ions in the solution phase.

The use of gypsum to counteract the adverse effects of surface crusts on seedling emergence has been widely recognized (Cary and Evans, 1974). In Australia, application of 4.48 and 17.9 Mg gypsum ha^{-1} to a sodic soil planted with lowland rice increased the Ca:Na ratio of both soluble and exchangeable cations. Between 1963 and 1965, an estimated 44,500 ha of fallow soils were treated with gypsum to improve dryland wheat yields in the Wimmera and Southern Mallee districts of Victoria, Australia (Sims and Rooney, 1965).

Phosphogypsum has been effectively used in the USSR to reclaim solonetz and solonitizic soils, with 3.2 million Mg used in 1988 for this purpose. Its use is expected to reach 19.2 million Mg by the year 2000 (Novikov et al., 1990). Mishra (1980), summarizing phosphogypsum research in India, which began in 1973, concluded that up to 32 Mg ha^{-1} of Indian phosphogypsum, can be used safely for reclamation of sodic soils, despite the high F content. Oster (1980), assuming a ten-fold solubility of phosphogypsum over mined gypsum, demonstrated that rate and frequency of surface application would be different for phosphogypsum than for mined gypsum at a given electrolyte concentration and rate of water application.

BULK CARRIER FOR MICRONUTRIENTS AND LOW-ANALYSIS FERTILIZERS

Micronutrients B, Cu, Mn, Zn, and Fe are applied to soils to meet crop needs in relatively small amounts. Obtaining uniform distribution of small rates is difficult. This difficulty is surmounted by bulk-blending micronutrients with granular fertilizers. From 1950 to 1980, the market share of bulk-blended fertilizers increased from 0 to more than 50% of all classes of fertilizers.(Harre and White, 1985). It is expected to continue to increase as finer delineation of the fertility status of agricultural lands is achieved requiring more custom-analysis blended fertilizers. Bulk-blended fertilizers use high-analysis fertilizers such as urea for N, which for clay-coated agricultural grade is 46% N, triple superphosphate with 20% P, and potassium chloride with 48% K. Such environmental considerations as nitrates in drinking water and eutrophication of surface waters, due to enrichment from runoff leached by N & P fertilizers may necesitate the use of locally-blended low-analysis fertilizers applied more frequently than at present. Phosphogypsum, where readily available, provides a potential bulk carrier for micronutrients and low analysis fertilizer formulations. Phosphogypsum disked into the top 10 cm of soil at a rate of 112 Mg ha^{-1} had no adverse affect on yields of corn, wheat, or soybean (Mays and Mortvedt, 1986). Pelletized phosphogypsum, enriched with micro and macronutrients, has shown promise with urea and sulfate of potash magnesia (Hunter 1989) as pelletizing agents. Also, phosphogypsum mixed with urea at 2.3 times the weight of the latter has been found to reduce ammonia loss by 85% (Bayrakli, 1990).

CONCLUSIONS

Based on the review of the literature, phosphogypsum appears to be as good as mined gypsum as a source of S and Ca for crops (Alcordo and Rechcigl, 1993). In some cases surface application, appears to ameliorate subsoil Al toxicity and acidity in shorter time periods than lime. Phosphogypsum may prove to be superior to mined gypsum as an ameliorant for Al toxicity and as a conditioner for spodic soils, hard-setting heavy clay soils, and subsoil hardpans to improve saturated hydralic conductivity, surface and subsoil aggregation, and general structural development. Fluorides, which are notpresent in mined gypsum, help to detoxify Al, and acid impurities can increase the fluocculating and aggregating power of soil- and phosphogypsum-Al and -Fe, if properly exploited.

Also, phosphogypsum, where it is readily accessible, is a potential bulk carrier for micronutrients and low-analysis fertilizers. Increasing environmental demands to prevent contamination of ground water with nitrates and minimize applied N and P losses which promote rapid eutrophication of surface waters, may require the use of low analysis fertilizers in commercial agriculture as they are now commonly used in recreational and residential lawns and gardens.

Radionuclides, heavy metal impurities, and other pollutants in the order of magnitudes found in Florida phosphogypsum do not appear to constitute environmental hazards to surficial ground water, ambient atmosphere, crop tissue, or soil at rates normally used in agriculture. Based on currently available information, phosphogypsum appears to be environmentally safe as a source of S and Ca in crops and for other described uses in agriculture.

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