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LITERATURE REVIEW ON GYPSUM AS A CALCIUM AND SULFUR SOURCE FOR CROPS AND SOILS IN THE SOUTHEASTERN UNITED STATES

Prepared by
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Literature Review on

GYPSUM AS A CALCIUM AND SULFUR SOURCE FOR CROPS AND SOILS IN THE SOUTHEASTERN UNITED STATES

Reconciliation of Literature Review with EPA's Final Rule on Phosphogypsum

Prepared for

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by

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Perspective

Among the scientific investigators that have worked with it, phosphogypsum - with all its faults - has been looked upon as a major raw material asset for the state of Florida and it was with a sense of shock, and even disbelief, when these researchers learned that the USEPA had banned the use of this potentially useful and valuable material. This sense of disbelief became even more pronounced when the details of the logic for the ban became known.

It was immediately apparent to those who work in agriculture that something was seriously wrong with the phosphogypsum application rates assumed by the USEPA and used as the basis for the ban on agricultural use. While the risk calculations themselves appear to be unrealistic and are the subject of ongoing investigations, there was little or no doubt that the agricultural phosphogypsum application rates were significantly overstated. This publication is intended to address that aspect of the USEPA ruling that banned phosphogypsum use.

It is our belief, supported by what we accept as sound scientific evidence, that this ban is unnecessary and results in significant economic penalties to the state of Florida for both agriculture and road building. We will continue working in this area to develop factual information that will either refute or support the USEPA assumptions used as a basis for prohibiting phosphogypsum utilization.

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EXECUTIVE SUMMARY

Preamble

In 1992, the Environmental Protection Agency (EPA) banned the use of phosphogypsum containing more than 10 pCi $^{226}Ra\ g^{-1}$ for application to soils (Environmental Protection Agency, 1992). This ban was based on calculations of risk assessment on the assumption that phosphogypsum would be applied to a given soil at a rate of 2700 lb ac^{-1} biennially for 100 years. As will be shown in this report, this assumption is incorrect. The Fertilizer Institute unsuccessfully challenged the Final Rule made by the EPA who contended that this application rate truly reflected the likely usage of phosphogypsum in agriculture.

Introduction

Gypsum is used in agriculture for the following purposes:

- as an ameliorant for sodium-affected (sodic) soils which occur mainly in arid areas and is therefore of minor interest in this report,
- as a source of the nutrients calcium (Ca) and sulfur (S) required by all crops,
- as an ameliorant for the subsoil acidity syndrome which commonly afflicts soils in the Southeast, and
- as an ameliorant for crust and seal formation at the soil surface, a condition commonly encountered in the sandy textured soils of the Southeast.

This report has been prepared for the Florida Institute of Phosphate Research (FIPR) with the following objectives:

- to independently assess the published experimental evidence on gypsum use in agriculture in the Southeastern United States and in Florida in particular, and
- to compare the gypsum application rate assumed by the EPA in their calculations to actual field practice by computing both on a lb $ac^{-1}\ yr^{-1}$ basis.

To achieve these objectives, a thorough literature review was undertaken in an attempt to survey all citations so that the final outcome cannot be contested on the basis of a limited data set.

Calcium (Ca) Requirements of Crops

The following are the essential roles Ca plays in the nutrition of all plants:

- serves vital functions in the development of cells,
- is essential for membrane integrity and functioning of hormones,
- aids in the signalling of environmental changes, and
- partially offsets the toxic effects of aluminum (Al).

The amounts of Ca required to be present in soil by various crops can differ widely and in circumstances where soil Ca levels are low, gypsum is often used to remedy this deficiency.

Peanuts

The major crop in the Southeast for which Ca is most critical, is the peanut *(Arachis* hypogea) which has received most attention in the literature. The responses obtained in the field have served as the basis for the development of State Recommendations by the Cooperative Extension Service for the application of gypsum to peanuts. Research has clearly demonstrated that substantial benefits are to be derived from rotating peanuts with other crops which are not susceptible to peanut pests. This is by far the cheapest and most effective way of controlling peanut pests in the field. Consequently, the Cooperative Extension Service in all southeastern states advises farmers to rotate peanuts with other crops on a routine basis. Rotation of peanuts in a 2- or 3-year rotation is practiced by over 75% of the farmers in the Southeast. Therefore, the gypsum application rates recommended by the various states in Table S1 must be divided by 2 or 3 depending in whether peanuts appear every other year or every third year in the rotation. Rotational considerations do not appear to have been taken into consideration in the EPA's Ruling. Indeed, very few peanut farmers would ever be foolish enough to plant peanuts continuously on the same piece of land. As the literature review undertaken in this treatise indicates that these application rates are based on sound scientific data, they should be used as the basis for calculating an annual gypsum application rate. This aspect of peanut production was not apparently considered by the EPA in arriving at the Final Rule on Phosphogypsum.

On a whole field basis (broadcast application), the highest gypsum rate recommended for peanuts in the Southeast is 1720 lb gypsum ac^{-1}. Taking the most conservative approach assuming that peanuts are grown in a two-year rotation (practised by only one-third of peanut farmers on average), the maximum recommended rate on an annual long-term basis would be 860 lb ac^{-1} yr^{-1}. Because there is substantial financial gain to be achieved by growing peanuts in a three- over a two-year rotation, many farmers follow a three-year rotation system which would reduce this figure to 573 lb gypsum ac^{-1} yr^{-1}. Thus by comparison with the maximum rate at which gypsum would ever be applied in practice on a long-term basis to a given field (860573 lb gypsum ac^{-1} yr^{-1}), the figure of 1350 lb gypsum ac^{-1} yr^{-1} used by the EPA in their risk assessment calculations is too high by a factor of between 1.56 and 2.35.

However in many cases, farmers usually band place gypsum because this is much more economical as only between 1/3 and 1/2 of the amount is required. As a result the most likely rates at which gypsum would be applied to most production fields in any one year would be between 250 and 860 lb gypsum ac^{-1} yr^{-1} (Table S1). Consequently, the actual long-term rates would lie between 125 and 430 for a two- and 83 and 267 lb gypsum ac^{-1} yr^{-1} for a three-year rotation system. Thus in the most likely case, the EPA figure overestimates actual field practice by a factor between 3.1 and 16.3.

Table S1 Recommended gypsum rates for peanuts in the Southeast (Hodges et al., 1994)

State	Type	Soil Ca	Gypsum recommendation			
			lb ac^{-1}		kg ha^{-1}	
			Band†	Broadcast	Band	Broadcast
Alabama	Runner	Low	250*		280	
		Low	500		560	
		Med	250		280	
Florida	Virginia	All	800	1600	898	1795
	Runner, Spanish-seed	All	400	800	449	896
	Runner, Spanish	Low	400	800	449	896
Georgia§	Virginia	All	688-860	1376-1720	772-956	1544-1913
	Runner, Spanish-seed	All	344-430	688-860	386-483	772-965
	Runner, Spanish	Low	344-430	688-860	386-483	772-965
North Carolina	Virginia	All	600-800	1200-1600	673-897	1346-1795
South Carolina	Virginia	All	600-800	1200-1600	673-897	1346-1795
	Runner, Spanish	All	400-500	800-1000	449-561	898-1122
Virginia	Virginia, Seed	All	600	900-1500	673	1010-1683

† Band widths vary by State: Alabama = 30 cm (12 in); Florida, Georgia, North Carolina, South Carolina = 45 cm (18 in); Virginia = 50 cm (20 in)
§ Values for Georgia have been converted from Ca to equivalent pure $CaSO_4.2H_2O$
* When lime is applied

Assuming that half the farmers would broadcast phosphogypsum in a 2-year rotation and half would band place phosphogypsum in a 3-year rotation, the maximum average rate over all situations would be (860+267)/2 = 563 lb gypsum ac^{-1} yr^{-1}. The maximum, most likely and minimum rates of gypsum application are presented below:

- ***Maximum Rate***: 600 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate:*** 125-430 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate:*** 0-83 lb phosphogypsum ac^{-1} yr^{-1}

Tomatoes and Other Vegetable Crops

Tomatoes and peppers also have a definite requirement for Ca to reduce the incidence of blossom-end rot that can take a heavy toll on the quality of the crop. However in most cases, leaf sprays of Ca salts in minute amounts are highly effective and seldom if ever would gypsum applications be made to the soil. Only two States (Georgia and Tennessee) have gypsum recommendations for soil application ranging from 430 to 860 lb ac^{-1}. Because vegetable crops are highly susceptible to a wide range of diseases, rotations with other more resistant crops would always be practised by farmers for phytopathological control. Consequently, the most likely long-term annual rates would range between 215 and 430 for a two- and 143 and 287 lb ac^{-1} yr^{-1} for a three-year rotation. These values are between 3.1 and 9.4 times lower than the assumed EPA figure of 1350 lb ac^{-1} yr^{-1}. The maximum, most likely and minimum rates of gypsum application are presented below:

- ***Maximum Rate***: 430 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate:*** 200-300 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate:*** 0-143 lb phosphogypsum ac^{-1} yr^{-1}

Sulfur Requirements of Crops

Sulfur (S) which is an essential element for plant growth, is a constituent of a number of amino acids and is therefore required for protein synthesis. Crops take up between 10 and 20 lb S ac^{-1} for normal growth. Extensive experimentation has been carried out in all States in the Southeast to determine the rate of soil-applied S for optimal crop production, and forms the basis of the State Recommendations complied by the Cooperative Extension Service. These recommendations which have been converted to an equivalent gypsum basis, are summarized in Table S2.

Table S2 Recommended rates of gypsum application to crops in the Southeast to supply the essential element sulfur (S)

State	Crop	Gypsum Rate ($lb\ ac^{-1}$)
Alabama	All	54
Florida	Agronomic, grass	80-108
Georgia	All	54
North Carolina	Corn, small grains, cotton, tomato, bermudagrass	108-161
South Carolina	All	54

Thus, the maximum recommended gypsum rate for any crop is 161 lb ac^{-1} yr^{-1} which is more than eightfold lower than the rate (1350 lb ac^{-1} yr^{-1}) assumed by the EPA in their risk assessment calculations. The maximum, most likely, and minimum rates of gypsum application as a source of S are presented below:

- ***Maximum Rate***: 161 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate:*** 50-80 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate:*** 0 lb phosphogypsum ac^{-1} yr^{-1}

Gypsum for Subsoil Acidity Amelioration

Only a limited amount of research has been conducted in the Southeast to study the beneficial effects of gypsum on soils with acid subsoils where root penetration is limited. Most of the research has been confined to Georgia where a single 2.2-4.4 t gypsum ac^{-1} application has resulted in substantial yield responses which have been sustained over a long period of time. Because the longevity of this effect is in excess of 10 years, the recommended rate on an annual basis would be 400-800 lb gypsum ac^{-1} yr^{-1} which is at least 1.7-fold less than the assumed EPA value. At present, very few farmers have attempted this amelioration strategy and because of the high initial cost in excess of \$175 ac^{-1}, only very limited acreage devoted to highly remunerative crops is likely to be used in this cropping system in the future. The maximum, most likely, and minimum rates of gypsum application for the amelioration of subsoil acidity are presented below:

- ***Maximum Rate***: 800 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate:*** 400 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate:*** 0 lb phosphogypsum ac^{-1} yr^{-1}

Gypsum as an Ameliorant for Soil Physical Properties

Reclamation of Sodic Soils

Although sodic soils which are common in arid areas, do not occur to any appreciable extent in the Southeast, a brief overview of the gypsum requirements of these soils was undertaken because the EPA's Final Rule incorporated gypsum application rates for this purpose. The applications rates used in determining the Final Rule were based on commonly used rates and did not take the total amount required for reclamation into consideration. Based on a review of field reclamation studies, applications of between 7 and 35 t gypsum ac^{-1} would be required to reclaim the top 20 in (which is sufficient rooting depth for most crops under irrigation) of a highly sodic soil (exchangeable sodium percentage [ESP] =30) . On an annual basis, this would correspond to applications between 140 and 700 lb gypsum ac^{-1} yr^{-1} over a 100-year period which is between 2- and 10-fold less than the EPA assumed value. However in certain cases, applications in excess of these amounts have been made to certain soils, but these cases represent the exception rather than the rule.

If the biennial application rate (2700 lb phosphogypsum ac^{-1}) used by the EPA in arriving at the Final Rule was applied to a sodic soil over a 100-year period, this would amount to an application rate of 68 t ac^{-1} which is approximately twice the rates commonly used in practice. The maximum, most likely, and minimum rates of gypsum application for the reclamation of sodic soils are presented below:

- ***Maximum Rate*:** 700 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate*:** 200-500 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate*:** 0-200 lb phosphogypsum ac^{-1} yr^{-1}

Crusting and Seedling Emergence

Most of the research in the Southeast on this aspect of gypsum use has been conducted in Georgia where, as a result of reduced crusting, substantial improvements in water entry into soils have been obtained, thereby reducing runoff and erosion. Typically, applications ranging between 0.5 and 2 t gypsum ac^{-1} have proven to be highly successful and currently the Cooperative Extension Service recommends 0.5-1 t gypsum ac^{-1} for this purpose. Such applications are only recommended as an interim measure in the establishment of a permanent vegetative cover on highly erodible soils. Thus, this should be considered as an application that would be made once only or, at the most, once in five years in a no-till system. Relatively few farmers have adopted this technology at present as many consider it to be too expensive. However, if applications are made only over the row, the application rates would be reduced by a factor of 2-3.

Thus, the maximum amount of gypsum that would be applied over a 100-year period would not exceed 7-10 t ac^{-1}. The maximum, most likely, and minimum rates of gypsum application for the amelioration of crusting are presented below:

- ***Maximum Rate***: 200-400 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate:*** 100-200 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate:*** 10-50 lb phosphogypsum ac^{-1} yr^{-1}

Mechanical Impedence

Gypsum applications to the soil surface have been shown to reduce the mechanical impedence (resistance to root penetration) of subsoil horizons as a result of improved flocculation of the clay. A single 4.4 t ac^{-1} application of gypsum was sufficient for this purpose and the effect has lasted in excess of 10 years giving a long-term application rate of about 800 lb gypsum ac^{-1} yr^{-1}. Because of the high cost involved in the initial gypsum application, no farmers have yet attempted to use this strategy. The maximum, most likely, and minimum rates for this use are presented below:

- ***Maximum Rate***: 800 lb phosphogypsum ac^{-1} yr^{-1}
- ***Most Likely Rate:*** 400 lb phosphogypsum ac^{-1} yr^{-1}
- ***Minimum Rate:*** ? lb phosphogypsum ac^{-1} yr^{-1}

Environmental Impacts Associated with the Agricultural Use of Phosphogypsum

Application of a phosphogypsum with a high ^{226}Ra content (35 pCi g^{-1}) at the maximum rates for the different uses described above for a 100-year period would result in a maximum cumulative ^{226}Ra concentration of 1.57 nCi ^{226}Ra kg^{-1} of soil (58.0 Bq kg^{-1}) which is much lower than the 5 nCi ^{226}Ra kg^{-1} (185 Bq kg^{-1}) considered to be the upper limit of a safe range. Where phosphogypsum has been used as a source of Ca or S for crops, radiation added to the soil has, in all cases, not significantly increased native background levels. Even where a single rate of 4.45 t phosphogypsum (17.6 pCi ^{226}Ra g^{-1}) ac^{-1} was applied, no significant increases in ^{214}Pb, ^{214}Bi, or ^{226}Ra could be detected anywhere in the profile of two different soils to a depth of 3 ft, 5 years after application. No significant differences in plant uptake of these radionuclides could be detected due to phosphogypsum treatment. However in a leaching experiment on a very sandy soil, elevated ^{226}Ra concentrations were found in the leachate but these concentrations were well below the maximum allowed in drinking water.

Based on the scientific data, the conclusion can be drawn that there should be little concern associated with the use of phosphogypsum containing more than 10 pCi ^{226}Ra g^{-1} provided that Cooperative Extension Service application rates are used.

Conclusions

All the soundly based experimental data strongly suggest that the phosphogypsum rate of 1350 lb ac^{-1} yr^{-1} for 100 years used by the EPA as the basis for formulating the Final Rule on phosphogypsum use, is too high. A more appropriate maximum figure would be in the range 600-800 lb gypsum ac^{-1} yr^{-1} with the most likely application rate lying in the range 100-400 lb gypsum ac^{-1} yr^{-1}.

1. PREAMBLE

The Environmental Protection Agency (EPA) published the Final Rule on "National Emission Standards for Hazardous Air Pollutants (NESHAPS); National Emission Standard for Radon Emissions from Phosphogypsum (PG) Stacks" (Anon., 1992). This rule requires phosphogypsum to be disposed of in mines or stacks and furthermore prohibits:

(a) the use of this material for road construction,
(b) the soil application of PG that contains more than 10 pCi $^{226}Ra\ g^{-1}$, and
(c) the use of more than 700 lb of PG in each research and development project.

The Fertilizer Institute (TFI) prepared a Response to the Final Rule based on a document prepared by SENES Consultants, Ltd. (1992) that challenged the Final Rule. The essence of this challenge in terms of soil application can best be summarized by quoting directly from the Summary of this document.

> *Using dose/risk models and application scenarios described in the BID (Background Information Document), EPA concluded that 10 pCi g^{-1} is the maximum concentration of ^{226}Ra in PG that* can *be applied to soil while maintaining* an *acceptable level of risk at 3 x 10^{-4}. This value was calculated based on a biennial application rate of PG at the 95th percentile (2700 lb ac^{-1}) for 100 years. Using EPA's model, an incremental ^{226}Ra concentration of 0.44 pCi g^{-1} (0.44 nCi kg^{-1}) in soil at the end of 100 years was calculated in this study. Therefore, in the Final Rule, EPA has prohibited a practice on the basis that it results in* an *increase in ^{226}Ra concentration in soil of 0.44 pCi g^{-1} (0.44 nCi kg'). This is an interesting decision in view of EPA's acknowledgement in the Final Rule that natural ^{226}Ra concentrations in soil are known to range from 0.5 to 3 pCi g^{-1} (0.5-3 nCi kg').*
>
> *EPA estimated that the total risk to the reclaimer on agricultural land is approximately equally contributed by exposures to external gamma and indoor radon. If was shown in this report that 2the* (sic) *duration of exposure and consequently the total risk was overestimated by EPA by a factor of approximately 2.3 (30* years *instead of 70). Furthermore, the risk from external gamma* was *overestimated by EPA by approximately a* factor *of 2.5* and *the risk from indoor radon* was *overestimated by EPA by a factor of 3 or more. Therefore, the contribution to the total overestimate from these two components is* the average *of 2.5 and 3, ie. (sic) at least a factor of 2.75. When this is combined with the contribution from duration of exposure, the total overestimate is* at *least a factor of:*
>
> $$2.3 x 2.75 = 6.3.$$

EPA's decision on the reconsideration presented the following responses to the objections raised and for the sake of completeness, these have been quoted *verbatim* (Environmental Protection Agency, 1992):

TFI Objection:

> *The derivation of the presumptively safe level of 10 pCi g^{-1} ^{226}Ra for phosphogypsum used in agriculture is based on the 95^{th} percentile application rate of 2,700 lb ac^{-1} for 100* years. *Using the 90^{th} percentile rate, per Superfund policy, would be more appropriate. More importantly, the application rate of 2,700 lb ac^{-1} is for soil reclamation rather than soil productivity. Soil reclamation would not require applications at this rate over* a *100-year period. By combining the application rate for soil reclamation with the frequency rate for soil productivity the EPA has greatly overestimated the total phosphogypsum application that would occur over the 100-year period.*

EPA Response:

> *Superfund guidance is not necessarily applicable under this NESHAP. However, TFI has not correctly stated the Superfund guidance. That guidance for calculating reasonable maximum exposure calls for the choice of the 95th percentile values where available, or 90^{th} percentile values where 95^{th} percentile values are not available.*
>
> *The 95^{th} percentile application rate for phosphogypsum used in agriculture* was *calculated from data reported by TFI, based on a questionnaire they sent to users of phosphogypsum* (Docket A-79-11, XV-D-100A, Appendix, Tab 38). *The 95th percentile was based on considering application rates for a variety of crops produced in California and for peanut production in the South, based on the assumption that agricultural usage of phosphogypsum is about equally split between the (sic) California and the remainder of the U.S. Although the data from California show much higher application rates than those for peanuts, we do not believe that California's rates* are *necessarily associated with reclamation. Phosphogypsum is used for land reclamation in California; however, an expert on the use of phosphogypsum in California estimates that the application rate for reclamation is about 10,000 pounds per acre, considerably higher that (sic) the rates reported in the TFI questionnaire. He also estimates that the application rate for production is approximately equal to the rates reported in the TFI questionnaire* (Docket A-79-11, XVII-B-41).

Author's Comment:

On consulting Docket A-79-11, XV-D-100A, Appendix, Tab 38, one finds that these calculations were probably made on the assumption that the rates of gypsum listed under Question 2 would have been applied to peanuts on the same piece of land every year which, as will be seen later, is not a correct assumption (Section 3.1.6.2). Furthermore in Docket A-79-11, XVII-B-41, there are mistakes in Table 1 where gypsum application rates are given in $t\ ac^{-1}$ instead of lb ac^{-1}. What effect this has had on the calculations is unknown. In addition, the estimates of gypsum usage are based on currect short term use and are not based on direct experimental evidence in the reclamation of sodic soils. In the description of gypsum under the California section, the wrong impression is given that gypsum is used to reduce the salt content of sodic soils. Being a salt itself, gypsum, when added to a soil, actually increases the salt and divalent cation contents, which causes an improvement in the water transmission properties of a sodic soil. As a result, the elevated Ca concentration brings about the displacement of exchangeable Na (responsible for the poor physical properties of sodic soils) from the exchange complex. This Na can then be leached from the soil profile because the water transmission properties of the profile have been improved.

TFI *Objection:*

> *The assessment of agricultural use does not consider the differing application rates in different geographic areas of the country.*

EPA *Response:*

> *The risk analysis in the BID gives risks for various application rates. Use of the 95th percentile application rate to select a single value for the maximum permissible ^{226}Ra content in phosphogypsum distributed for agricultural use greatly simplifies compliance and enforcement procedures.*

This report was prepared at the behest of the Florida Institute of Phosphate Research to address whether or not the Environmental Protection Agency's 95th percentile biennial application rate of 2,700 lb phosphogypsum ac^{-1} for 100 years is, in fact, realistic in terms of documented responses of crops and soils to gypsum applications. The terms of reference indicated that the review of literature required to make this assessment be confined to the southeastern United States with the briefest general comment on maximum application rates for the reclamation of sodic soils.

As the author of the present review is not an expert in the field of risk assessment, no attempt will be made to cast judgement on any of the risk assessments made by the EPA. Rather the review will be confined to assessing all available published information concerning the use of gypsum in agriculture in the Southeast with the objective of determining maximum, as well as most probable, application rates for phosphogypsum application on crops in this region so that valid comparisons can be made with the EPA's assumed biennial application rate of 2,700 lb ac^{-1} for 100 years on which the Final Rule was based. In all cases unless otherwise indicated, all data presented were obtained under field conditions. The data have been presented in the units used in the original publications and in certain cases, the results have been recalculated into units commonly used in the United States or into other units to facilitate comparisons between different sets of data. In all categories of gypsum use, an attempt will be made to calculate the rate on a lb ac^{-1} yr^{-1} basis to make the data comparable to the 1350 (2700/2) lb ac^{-1} yr^{-1} used by the EPA in their calculations.

2. INTRODUCTION

Although it appears that the benefits to be derived from the use of gypsum ($CaSO_4.2H_2O$) have been known for many centuries in Europe (Alway, 1940) its use in the United States as a soil ameliorant and source of nutrients for plants (Crocker, 1945) dates from the first experiments of Benjamin Franklin in Virginia (Ruffin, 1835). Prior to the industrial revolution, mined gypsum was the only source available for use in agriculture but since the industrial revolution, many by-product gypsum sources have appeared on the market with phosphogypsum probably being the largest in terms of tonnage at present.

Gypsum has been used in four major applications in agriculture:

1. Its first use was on sodic soils as a corrective treatment to improve their very poor physical properties. Sodic soils occur in arid to semi-arid regions where accumulations of sodium (Na) have caused soil structural decline resulting from clay dispersion which, in turn, causes blockages in the pore continuity reducing the free movement of water in the soil profile. Application of large amounts of gypsum (5-60 t ha^{-1} = 2.23-26.7 short t ac^{-1}) to the soil which removes Na ions and supplies electrolyte to flocculate the clay, alleviates this adverse condition. This application probably accounts for the greatest usage of gypsum in agriculture but is of little importance in the Southeastern United States.

2. As a source of nutrients, gypsum has been proven to be an excellent source of calcium (Ca) and sulfur (S) for a wide range of crops such as peanuts, vegetables, forages, etc. throughout the world and in the Southeastern United States, in particular.

3. Recently, gypsum has been shown to counteract the negative effects of subsoil acidity on plant root development allowing crops to harvest water from subsoils previously beyond their reach. In this application which has resulted in

substantial crop yield increases in the Southeast, gypsum is used at rates of 5-10 t ha^{-1} (= 2.23-4.46 short t ac^{-1}) applied infrequently (once in 8-10 years).

4. The benefits of using gypsum to alleviate surface crust and seal formation on soils, generally throughout the world and in the Southeast in particular, has been clearly demonstrated over the past few years. In this application, gypsum reduces the formation of a crust or seal when the soil surface is exposed to the energy of impacting raindrops by promoting flocculation of clay particles. This use requires much lower rates of gypsum than for sodic soils.

The objective of this treatise is to:

(a) review the Ca, S, and gypsum requirements of crops and soils in the Southeast, generally, and in Florida in particular, so that the appropriate average annual rate of application of these materials (in lb ac^{-1} yr^{-1}) to soils can be established, and

(b) compare these rates converted to a gypsum equivalent with the rate used in calculating the risk assessment that resulted in the ban on the use of phosphogypsum containing radiation in excess of 10 pCi $^{226}Ra\ g^{-1}$ (370 Bq kg^{-1}).

In view of the need to obtain precise figures for the optimum rates of gypsum application to crops, it has been necessary to review the literature exhaustively. For this reason, the search has included the earliest published records on the use of gypsum and S- and Ca-containing fertilizers on crops in the Southeast. The rates of S and Ca used as nutrient sources can readily be converted to gypsum equivalents.

3. CALCIUM REQUIREMENTS OF CROPS

Calcium is taken up in relatively large quantities by crops but most is stored in insoluble forms as a constituent of cell walls. Only a small proportion remains metabolically active but serves vital functions in the development of cells, in the functioning of membranes and hormones, and in signaling environmental changes (Hanson, 1984). Typical contents of Ca in plant tissue range from as little as 0.1% in seeds to as high as 3-4% in the leaves of certain crops (Bartholomew, 1928). In most neutral soils (pH ~ 7), the levels of exchangeable and soluble Ca are sufficiently high to supply the requirements of most crops adequately. However in acid soils, levels of exchangeable and, particularly, soluble Ca are often quite low and sometimes labile aluminum (Al) is present at levels that are toxic to plants. Under such circumstances, the ameliorant of choice would be calcitic ($CaCO_3$) or dolomitic ($CaCO_3.MgCO_3$) limestone, both of which supply Ca and precipitate labile Al, thereby reducing its toxicity. On certain highly weathered soils, the application of large quantities of lime can be detrimental to the growth of certain crops as a result of induced deficiencies of essential elements such as

Zn, P, B, and Mn (Sumner et al., 1986a), or as a result of negative impacts on soil physical properties such as water infiltration (Kamprath, 1971) or on the promotion of diseases in certain crops such as potatoes. On the other hand, for certain crops such as peanuts (West, 1940), tomatoes (Raleigh and Chucka, 1944; Evans and Troxler, 1953; Marschner, 1986), tung nuts (Neff et al., 1954.; Lagasse et al., 1955; Neff et al., 1960), lettuce (Marschner, 1986) and apples (Marschner, 1986; Pavan and Bingham, 1986) where Ca plays an exceedingly important role in promoting crop quality, the levels of soluble Ca attained as a result of lime applications are often insufficient and consequently, crop quality may suffer. The reason why lime is inefficient in elevating soluble Ca in the soil solution stems from the fact that as the soil pH increases, there is a commensurate increase in the cation exchange capacity (CEC) to which the added Ca becomes attached leaving very little excess to increase the soil solution Ca concentration. It is under these circumstances that gypsum, being a relatively soluble salt, has a role to play in supplying elevated levels of Ca in the soil solution.

3.1 Peanuts

The importance of Ca in the development of peanut pods was originally recognized by Jones in 1885 who stated "Unless the soil contains a goodly percentage of lime in some form in an available state, no land will produce a paying crop of pods, although it may yield large, luxuriant vines". In most plants other than peanuts, Ca is supplied directly to all aerial parts of the plant by mass flow in the transpiration stream which is a continuous process during daylight hours being driven by the difference in water potential between the atmosphere and the soil. The quantity of Ca supplied to the plant by this mechanism is roughly equal to the product of the volume of water transpired and the concentration of Ca in the soil solution (Claasen and Barber, 1976). For most crops, mass flow usually supplies the plant with more Ca than it requires for metabolic purposes with the excess being deposited in the leaf as inert Ca oxalate or pectate. This explains why Ca deficiency is seldom observed when topsoils have been adequately limed. However for peanuts, the supply of Ca to the developing pods cannot take place by the normal mass flow process because, once the flower has been fertilized, the developing gynophore (pod) enters the soil where its water potential becomes equal to that of the roots in the bulk of the soil (Sumner et al., 1988). As a result, there is no driving force for mass flow to the gynophore. Consequently, the developing seed pod can now only receive the Ca required for its development by the process of diffusion which requires the establishment of a steep gradient in Ca concentration from the bulk of the soil solution to the interior of the pod (Smal et al., 1989). That this takes place was demonstrated as early as 1949 in Florida by Bledsoe et al. (1949). In the absence of adequate levels of soluble Ca in the soil, the pod cell walls do not develop normally often resulting in fungal attack by organisms such as *Pythium myriotylum* and *Rhizoctonia solani* which cause pod rot and severe losses in yield (Garren, 1964; Walker and Csinos, 1980). This is the reason why gypsum, being a moderately soluble salt, is applied to peanuts at flowering to increase the concentration of Ca in the soil solution to ensure adequate pod development and high yield (Smal et al., 1988; Sumner et al., 1988).

The earliest experiments with gypsum on peanuts in the Southeast were summarized by West (1940) and Killinger et al. (1947), a distillate of which is presented in Table 3.1. Responses were not uniform and varied from location to location with non-responsive sites being as frequent as responsive. A major problem with these early experiments was that the gypsum treatments were compared to controls on soils, many of which showed responses to other fertilizers. This tended to mask the gypsum responses. In addition, no statistical analyses were presented. However, these results were sufficiently encouraging to stimulate much research throughout the region.

Table 3.1 Peanut yield responses in early experiments with gypsum in the Southeast (West, 1940; Killinger et al., 1947)

State	Soil	Year	Gypsum Rate (lb ac^{-1})	Yield (lb ac^{-1})	
				No gypsum	Gypsum
Florida	Norfolk s†	1922	400	542	630
	Norfolk s	1923	600	1073	1073
Virginia	Onslow fsl	1931	165	850	960
Mississippi	Ruston ls	1939	400	368	469
	Norfolk ls	1939	400	617	742
North Carolina		1938-39	400	1192	1208
North Carolina	Ruston sl	1939	300	572	1294
	Portsmouth sl	1939	300	880	739
	Norfolk sl	1939	300	2130	2121
	Coxville sl	1939	300	1126	1117

† s = sand, fsl = fine sandy loam, ls = loamy sand, sl = sandy loam

3.1.1 North Carolina

In early experiments in North Carolina, Collins and Morris (1941) demonstrated large increases in peanut yield and shelling percentage where gypsum had been applied at rates of 200-400 lb ac^{-1}. However the responses were not consistent at all locations and in all years. Time of application appeared to have little effect. Burkhart and Collins

(1942) established that Ca was an indispensible nutrient throughout the growth of the peanut plant especially for seed development. Subsequently, Colwell and Brady (1945b), working with large seeded peanuts, obtained some spectacular responses to the application of 400 lb gypsum ac^{-1}. Very stong relationships were obtained between the number of cavities in pods which were filled and yield, on the one hand, and exchangeable Ca and Ca saturation before planting, on the other (Figure 3.1).

In addition, a gypsum application of 400 lb ac^{-1} at the fruiting (flowering) stage rather than at planting was much more effective in promoting yield, and was far superior to the use of limestone. Additions of potassium (K) or magnesium (Mg) sulfates or dolomitic limestone ($xCaCO_3.yMgCO_3$) were, in general, slightly detrimental to fruit filling or kernel development (Brady and Colwell, 1945). On low Ca soils, gypsum increased the number of seed cavities filled and the proportion of two-cavity fruit in large versus small seeded varieties (Colwell and Brady, 1945a; Reed and Cummings, 1948). Gypsum applied at 400 lb ac^{-1} increased the Ca content of the shells of all varieties studied (Colwell et al., 1945). Middleton et al. (1945) showed that the yield of peanut oil was promoted more in large seeded varieties than Spanish types by an application of 400 lb gypsum ac^{-1}. Reid and York (1958) demonstrated that it was the Ca, and not the S content of gypsum that was required for adequate peg development. Summarizing the experience in North Carolina during this period, Colwell et al. (1946) presented Figure 3.2 comparing average responses to 400 lb gypsum (landplaster) ac^{-1} on soils of different initial Ca contents. Gypsum was more effective than limestone on soils of low extractable Ca status.

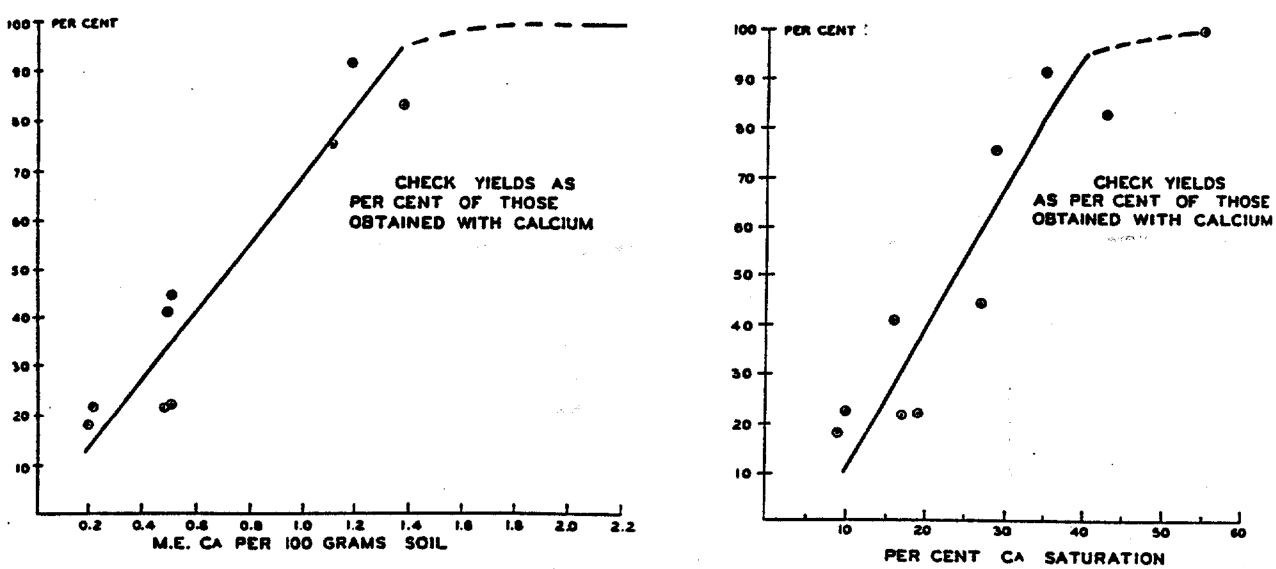

Figure 3.1 Relationships between (A) Soil Ca saturation (%) and proportion of cavities filled with peanuts (%) and (B) Exchangeable Ca and yield of peanuts (%) (Colwell and Brady, 1945b)

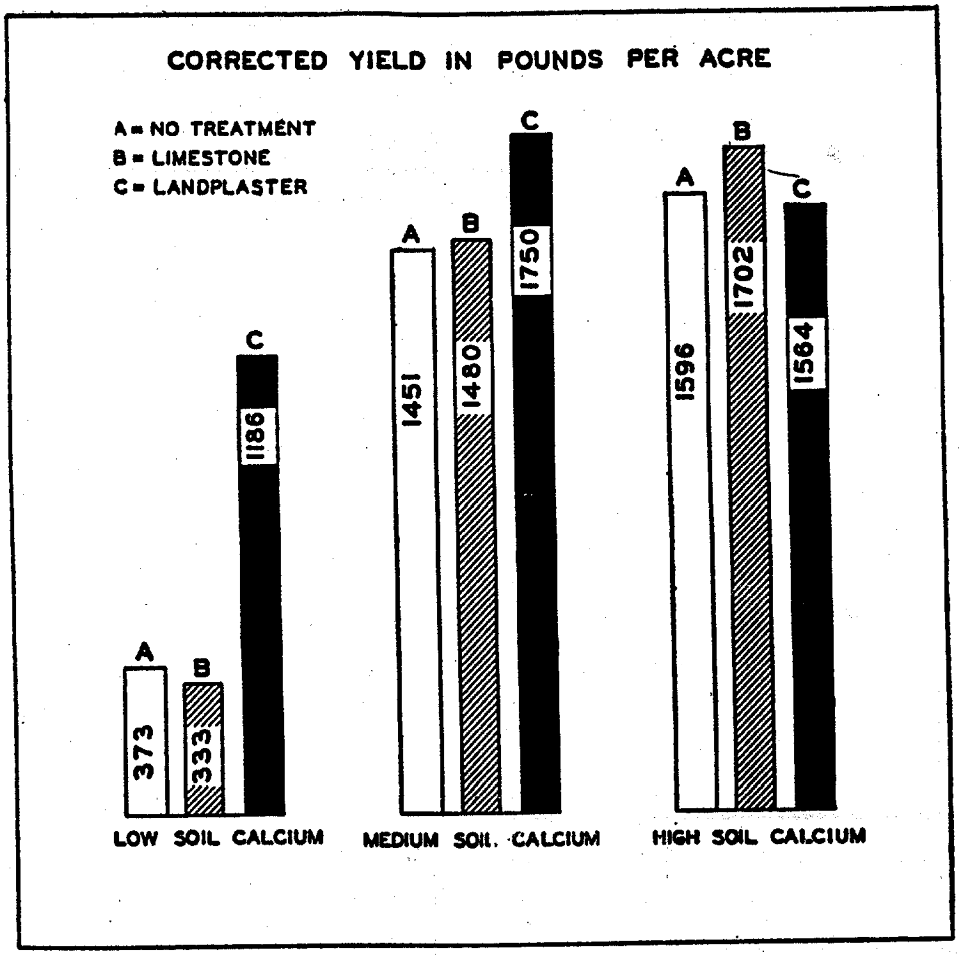

Figure 3.2 Peanut yield response to 400 lb gypsum (landplaster) ac^{-1} on soils of different initial soil extractable Ca level (Colwell et al., 1946)

Based on these data, Colwell et al. (1946) presented the following official recommendation of the North Carolina Agricultural Experiment Station for the use of gypsum on peanuts:

> *The soil must be moderately well supplied with calcium for the production of good yields of large type peanuts. .... On soils low to medium in calcium, add at least 400 lb of landplaster (gypsum) (per acre) to the foliage at early blooming stage. On soils high in calcium, the landplaster is not necessary. The calcium level can be determined best by having soil analyzed. Usually a soil is low in calcium if many 'pops' (unfilled pods) have been noticed in previous peanut crops. It is probably high in calcium if good quality nuts have been established in past years without calcium additions.*

Table 3.2 Effect of banded gypsum on yield and pod filling in large seeded Virginia peanuts grown on two soils of different initial exchangeable Ca level (Reed and Brady, 1948)

Treatment	Gypsum rate ($lb\ ac^{-1}$)	Yield ($lb\ ac^{-1}$)	Ovarian cavities filled (%)	Exchangeable Ca ($cmol_c\ kg^{-1}$)
Norfolk loamy sand				
Control	0	476	12.4	0.25
Gypsum at emergence	640	1051	86.8	
Gypsum at early bloom	640	1162	79.1	0.60
$LSD_{0.05}$		240	11.5	
Bradley sandy loam				
Control	0	1118	88.5	0.80
Gypsum at emergence	640	1184	87.1	
Gypsum at early bloom	640	1204	90.1	1.50
$LSD_{0.05}$		269	ns	1.50

Subsequently, Reed and Brady (1948) confirmed the above findings pointing out that responses to gypsum (640 lb ac^{-1}) were likely only on soils low in exchangeable Ca and that the yield increases were due to a combination of more developing pods which were better filled with sound mature kernels (Table 3.2). Concealed kernel damage was shown to be due to a lack of Ca in the pegging zone (Cox and Reid, 1964). These results emphasize that adequate levels of labile Ca must be present in the pegging zone as the gynophores develop. Indeed, applications should be made to every crop of peanuts on soils with low extractable Ca as the carry-over effect from year to year is negligible.

This excellent work in North Carolina apparently answered most of the pressing questions on the Ca nutrition of peanuts because little further work was conducted until 1964 when Cox and Reid (1964) demonstrated that gypsum applications (63 and 126 lb S ac^{-1} = 270 and 540 lb gypsum ac^{-1}) in conjunction with boron (B) were effective in suppressing concealed damage in peanuts (damage that cannot be seen until the kernel is split to expose the plumule and inner faces of the cotyledons). They demonstrated that this damage was more closely related to the concentrations of Ca and B in the kernels than to the levels of these nutrients in the leaf tips. Subsequently, Sullivan et al. (1974) in an effort to minimize the cost of gypsum applications to peanuts studied the effects of gypsum rates on peanut yield and quality at four sites with initial exchangeable Ca levels ranging from 0.8 to 2.35 $cmol_c$ kg^{-1} (Table 3.3).

Table 3.3 Effect of banded gypsum rates on yield and quality of peanuts grown over four sites and corresponding soil Ca levels after treatment (Sullivan et al., 1974)

Gypsum kg ha^{-1}	Yield kg ha^{-1}	SMK[§] %	ELK[¶] %	Seed Ca %	Dark plumule %	Seedling survival %	Soil Ca $cmol_c$ kg^{-1}
0	2782 (2477)	62.7	37.6	0.045	19.8	58.9	1.27
673 (600)[†]	3440 (3063)	75.6	51.9	0.068	2.1	88.4	1.72
1346 (1200)	3521 (3147)	76.1	50.8	0.085	1.7	90.7	2.15
$LSD_{0.05}$	200 (178)	2.6	2.7	0.006	2.6	3.6	0.16

[§] SMK = Sound mature kernels; [¶] ELK = Extra large kernels; [†] Value in () is in lb ac^{-1}

As significant responses were only obtained at the low rate of gypsum application, these data indicate that 673 kg gypsum ha^{-1} (600 lb ac^{-1}) is sufficient in order to maximize yield, SMK, ELK and reduce dark plumule to an acceptable level. On the other hand, Daughtry and Cox (1974) found that 3 commercial gypsum materials applied at 760 kg ha^{-1} (675 lb ac^{-1}) at flowering produced no differences in the yield of Florigiant peanuts.

Thus in North Carolina, the highest rates of gypsum to which yield responses have been recorded are of the order of 650-700 lb ac^{-1} while, in many cases, no responses were observed. Clearly the rate of gypsum to be applied to a peanut crop is a function of the level of Ca in the soil at flowering but even under the most severe Ca limiting conditions, applications in excess of 700 lb ac^{-1} are not supported by the scientific data.

3.1.2 Virginia

In Virginia, Garren (1964) demonstrated that 800 lb gypsum ac^{-1} applied at peak flowering was almost as effective as 8000 lb ac^{-1} applied preplant in supressing pod rot and promoting yield of Virginia Bunch peanuts. In a later popular article, Garren (1966) concluded that 10-fold or even 5-fold increases in the rate of applying gypsum over the

800 lb ac^{-1} are not necessary to control pod breakdown effectively, but then went on to suggest using rates of 2000-3000 lb ac^{-1}. The reason for this contradiction is not clear, but it should be pointed out that he is a plant pathologist and was interested in the disease aspects of the problem, rather than accurately assessing the exact Ca requirements of the crop. For this reason, his suggested levels of 2000-3000 lb gypsum ac^{-1} which were not supported by data, should be discounted.

Subsequently, Hallock and Garren (1968) found that peanut pods having Ca concentrations > 0.20% were more resistant to pod rot than those containing < 0.15% Ca. However, the responses in terms of yield and incidence of pod rot to above normal rates of gypsum application (3090 kg ha^{-1} = 2750 lb ac^{-1}) were recorded in only one out of three years. In agronomic terms, erratic responses of this nature tend to be down played.

With minor exceptions, the Virginia data support application rates for gypsum of 540 lb ac^{-1} band placed over the row or 800 lb ac^{-1} broadcast over the entire field.

3.1.3 Florida

The earliest recorded experiments on gypsum in peanuts in Florida demonstrated that modest responses were possible (Killinger et al., 1947). Harris (1949) showed that few fruit developed in the absence of Ca in the pegging zone while Bledsoe and Harris (1950) found that, while the root was the primary absorbing organ of the plant for nutrients, the gynophore, once pegged into the soil, was responsible for a large part of the Ca in the developing pod. In an experiment in which rooting and fruiting zones were kept separate, Harris (1956) demonstrated that if Ca was withheld from the fruiting zone but not the rooting zone, yields suffered greatly but, in the reverse situation, no effect on yield was observed. He also showed that the response to gypsum was due to the Ca and not the S present. Robertson et al. (1965a & b) and Robertson and Lundy (1960) conducted work on sandy Florida soils. Their results are summarized in Table 3.4.

In both cases when soil Ca was low (Experiments I and III), significant yield increases to gypsum application were recorded. There were no statistically significant benefits from gypsum applications in excess of 350 lb ac^{-1} in any experiment. When soil Ca was high (Experiment II), no yield responses to gypsum application were recorded.

A little later, Moore and Wills (1974) found no relationship between gypsum applications at 897 and 1793 kg ha^{-1} (800 and 1600 lb ac^{-1}) and pod rot in an artificial medium. Hallock (1973) showed that 2000 lb gypsum ac^{-1} decreased pod rot and increased crop value by \$65 ac^{-1} in large seeded Virginia type peanuts. In the late 70s Hallock and Allison (1980a & b) studied responses to different types, rates, methods and times of application of gypsum at two sites having very similar initial extractable soil

Table 3.4 Peanut yield parameters and post-harvest soil Ca values from three experiments with gypsum conducted on Lakeland fine sand (Robertson et al., 1965a & b; Robertson and Lundy, 1960)

Gypsum (lb ac^{-1})	Unshelled Nuts (lb ac^{-1})	SMK[§] (%)	ELK[¶] (%)	Empty pods (100s ac^{-1})	Soil Ca (lb ac^{-1})
		Experiment I			
0	1610	68	27		63
350	2030**	65	26		102
		Experiment II			
0	1940				284
300	2090				398
600	2230				364
		Experiment III			
0	1985	66	39	2904	87[†]
300	2230**	68	41	1336	74[†]
600	2197**	70	42	1307	80[†]

[§] SMK = Sound mature kernels; [¶] ELK = Extra large kernels; ** Significantly different than the control at 1% level of probability; [†] Pre-gypsum application values

Ca levels (~ 550 kg ha^{-1}≡ 490 lb ac^{-1}) (Table 3.5). On the Kenansville soil, there were no responses in either yield or value to increasing gypsum rate above 605 kg ha^{-1} (540 lb ac^{-1}) whether band placed over the row or broadcast nor did timing have any significant effect. However, on the other hand on the Rumford soil, there was a small but significant increase in yield to 907 kg gypsum ha^{-1} (800 lb ac^{-1}) broadcast versus 605 kg ha^{-1} (540 lb ac^{-1}) band placed at the latest application time, but this did not translate into a significant increase in crop value. The different types of gypsum had little or no effect on yield and quality (data not presented). These results would support a gypsum application rate of only 605 kg ha^{-1} (540 lb ac^{-1}) band-placed under these conditions.

Harris and Brolmann (1963) reduced dark plumule incidence to zero and increased yields of Florigiant peanuts as a result of applying 600 lb gypsum ac^{-1} to an Arredondo loamy fine sand. Harris and Brolmann (1966a & b) obtained significant yield increases of Florigiant peanuts on a Lakeland fine sand when 350 lb gypsum ac^{-1} was applied. The yield response was largely due to the increased number of plump normal seeds and a reduction in one compartment pods. In subsequent experiments in Florida, Harris and Brolmann (1966c) found no significant yield or quality responses in Florunner and Florigiant peanuts to the application of 896 kg gypsum ha^{-1} (≡ 800 lb ac^{-1}) on an Arredondo fine sand which is not surprising in view of the high initial soil exchangeable Ca level of 296 ppm (~592 lb ac^{-1}).

Table 3.5 Peanut yield and value responses at two sites to rates, timing, and method of gypsum application (Hallock and Allison, 1980a&b)

Gypsum Treatments			Yield (kg ha^{-1})	Crop Value ($)
Method	Date	Rate (kg ha^{-1})		
Kenansville loamy fine sand				
Control	-	0	2235b† (1990)	682c
Band	6/2	605 (540)¶	3510a (3125)	1571a
		1210 (1080)	3510a (3125)	1556a
Broadcast	6/2	907 (800)	3090ab (2751)	1336ab
		1814 (1600)	2980ab (2653)	1262ab
Band	6/29	605 (540)	3535a (3147)	1526ab
		1210 (1080)	3415a (3040)	1334ab
Broadcast	6/29	907 (800)	3395a (3023)	1363ab
		1814 (1600)	3125ab (2782)	1321ab
Rumford loamy fine sand				
Control	-	0	2655d (2364)	1109d
Band	5/25	605 (540)	3225abcd (2871)	1408abcd
Broadcast	5/25	907 (800)	3380abc (3009)	1485abc
Band	6/15	605 (540)	2920cd (2600)	1255cd
Broadcast	6/15	907 (800)	3405abc (3031)	1484abc
Band	6/30	605 (540)	2935cd (2613)	1324bcd
Broadcast	6/30	907 (800)	3770a (3356)	1638ab

† Treatment means followed by all unlike letters are significantly different at the 5% level;
¶ Values in () are in lb ac^{-1}

Again, experimental data in Florida show that responses of peanuts to gypsum are likely to be achieved only on soils where the initial soil Ca levels are low. The Florida data would support application rates for gypsum between 350 and 600 lb ac^{-1} in bands depending on variety.

3.1.4 Alabama

Early experiments on peanuts in the 1950s demonstrated responses to 400-500 lb gypsum ac^{-1} (Scarsbrook and Cope, 1956). During the late 60s and early 70s, a large number of experiments were conducted in Alabama to assess the response of peanuts to lime and gypsum (Hartzog and Adams, 1973). The results were clear and consistent: (a) when the soil test Ca was above 200 lb ac^{-1} (medium), there was no response to gypsum, (b) responses to gypsum were recorded on all soils with a Ca soil test (Mehlich I) below 175 lb ac^{-1} (low) with only one exception, and (c) variety had no influence on whether gypsum was needed or not. Unfortunately, no indication of the amount of gypsum applied in these experiments was presented. In a subsequent set of experiments designed to obtain more precision in the gypsum recommendations in which gypsum at 500 lb ac^{-1} was applied in replicated plots in farmers fields, Hartzog and Adams (1988) found no evidence for applying gypsum to soils testing higher than 220 lb Ca ac^{-1} by the Auburn Soil Test Method (Mehlich I) (Table 3.6).

They further established that there was little evidence for the 500 lb gypsum ac^{-1} recommendation tested (Table 3.7). In fact on soils testing 290 lb Ca ac^{-1} or higher, no responses in yield or grade were recorded for Florunner peanuts above a gypsum rate of 250 lb ac^{-1}. These data clearly emphasize the need for knowledge of soil Ca levels in determining whether responses to gypsum are likely. It is only on soils testing low in extractable Ca that responses are likely to be recorded. In the same set of experiments, different sources of gypsum were found to have the same effect on peanut yield and quality.

Subsequent work by Adams and Hartzog (1991) has shown that when the crop is being produced for seed purposes, gypsum may be required to increase the level of soil Ca above that (280 kg Ca $ha^{-1} \equiv$ 250 lb ac^{-1}) at which maximum yields and SMK values for Runner type peanuts have been obtained. Above extractable Ca levels of 400 kg ha^{-1} (350 lb ac^{-1}), there were no further responses to gypsum application in terms of germination and seedling survival. These findings were corroborated by Adams et al. (1993) over 14 sites with a wide range of extractable Ca levels and for four Runner cultivars.

Thus, the Alabama data for optimal gypsum rates for peanuts determined in the field in an extensive program of experimentation over many years suggest that the rates established in North Carolina, Virginia, and Florida might even be slightly on the high side. The Alabama data would only support maximum gypsum rates of between 250 and 500 lb ac^{-1} depending on extractable Ca levels at flowering.

Table 3.6 Yield and grade (sound mature kernels [SMK]) responses of various peanut varieties to 500 lb gypsum ac^{-1} applied at the early bloom stage in Alabama (Hartzog and Adams, 1988)

Soil Ca Range (lb ac^{-1})	# of Sites	# of Sites Responding	Average Yield (lb ac^{-1})		Grade (%)	
			No gypsum	Gypsum	No Gypsum	Gypsum
Florunner Variety						
0-110	5	5	1330	2530	63	71
120-200	12	7	1989	2751	66	73
210-300	10	0	3067	3129	71	73
310-1140	17	0	3547	3258	71	71
Sunrunner Variety						
0-210	2	2	2420	3830	59	70
220-780	5	0	3816	3830	74	75
NC-7 Variety						
0-200	2	2	815	3420	36	66
340-1000	6	0	3892	3852	70	71
Florigiant Variety						
130	1	1	380	2470	52	66
Early Bunch Variety						
420-440	2	0	3370	3325	59	67
GK-3 Variety						
460-1030	2	0	4000	4065	66	66
GK-7 Variety						
330-410	2	0	3410	3590	76	77
Sunbelt Runner Variety						
270	1	0	4580	4310	71	73

Table 3.7 Effect of gypsum rate on yield and grade of Florunner peanuts in relation to soil test Ca level (Hartzog and Adams, 1988)

Soil	Soil Test Ca (lb ac^{-1})	Yield (lb ac^{-1})			Grade (%)		
		Gypsum Rate (lb ac^{-1})			Gypsum Rate (lb ac^{-1})		
		0	250	500	0	250	500
Troup ls	100	1010b†	2340a	2880a	66B†	74A	73A
Poarch sl	120	1840b	2300a	2160ab	67B	75A	75A
Fuquay ls	140	1330b	2330a	2310a	66B	75A	75A
Bonifay ls	140	1240b	2690a	2620a	60B	72A	72A
Americus ls	140	1219b	2630a	2870a	57B	64A	64A
Bonifay ls	290	2870a	2890a	3200a	76A	77A	77A
McLaurin ls	360	2400a	2420a	2270a	66A	68A	69A

† Means in a row followed by the same letter are not significantly different at the 10% level of significance

3.1.5 Georgia

In the earliest reported experiments in Georgia, Bailey (1951) found that gypsum greatly increased the yield of large-seeded Virginia peanuts and slightly increased those of Spanish type (Table 3.8). As a result, the official State recommendation at that time was the application of 400-500 lb gypsum ac^{-1} directly on top of the plants at full bloom.

Table 3.8 Effect of 500 lb gypsum ac^{-1} on yield of four varieties of peanuts (Bailey, 1951)

Variety	Average yield of pods (lb ac^{-1})		
	No gypsum	Gypsum	Increase from gypsum
Small Spanish	1193	1339	146
NC Runner	1156	1602	446
Virginia Bunch	980	1914	934
Virginia Bunch (NCS 31)	741	2034	1293

Herndon (1965) found no yield response to varying rates of gypsum (0, 500, 1000, 1500 lb ac^{-1}) applied to four cultivars (Florigiant, Virginia Bunch 67, Early Runner and Argentine) on an unspecified soil at Tifton but there was a slight improvement in the crop value at the 500 lb ac^{-1} rate compared to the control. Nevertheless in 1973, the recommended rate for gypsum application (McGill and Henning, 1973) was 896-1121 kg ha^{-1} (800-1000 lb ac^{-1}) for Virginia type regardless of Mehlich I Ca level and 448-560 kg ha^{-1} (400-500 lb ac^{-1}) for Spannish and Runner type peanuts. The basis for this recommendation is unknown but appears to be for "insurance" because the literature in Georgia and other states at the time would support only applications of 336 to 898 kg ha^{-1} (300-800 lb ac^{-1}) on soils low in Ca. In support of the lower gypsum rate, Walker (1975) obtained a significant yield and SMK response to 663 kg gypsum ha^{-1} (600 lb ac^{-1}) in Florunner peanuts on a Tifton soil.

Subsequently, Walker and Keisling (1978) studied the differential responses of different cultivars (Florunner, Tifrun, Florigiant, NC-FLA 14 and Early Bunch) to the currently recommended high rate of 1121 kg gypsum ha^{-1} (1000 lb ac^{-1}) and found no response on a Greenville sandy loam soil with a Mehlich I Ca level of 818 kg ha^{-1} (728 lb ac^{-1}). However on a Fuquay loamy sand with a Mehlich I Ca level of 215 kg ha^{-1} (191 lb ac^{-1}), yield responses were obtained for all cultivars except Florunner (Figure 3.3) while, in most cases, gypsum application increased SMK, ELK, and seed oil content. On Early Bunch peanuts, Walker et al. (1979) obtained significant yield, SMK, and ELK

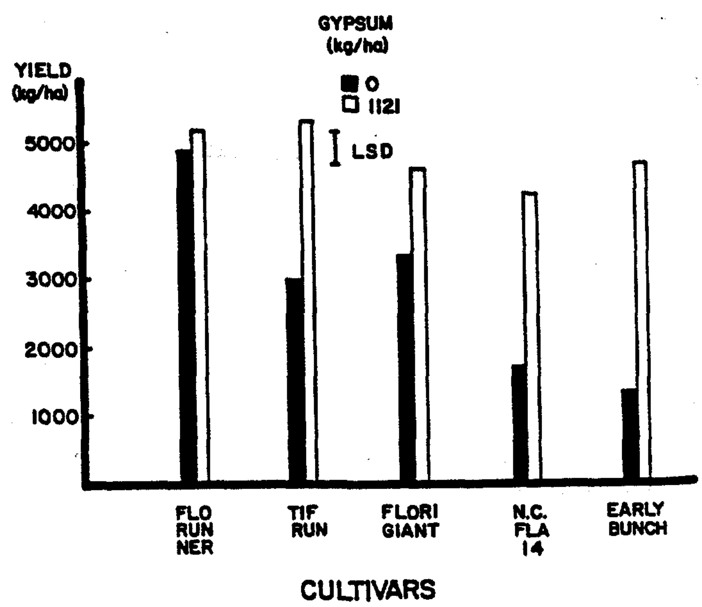

Figure 3.3 **Yield responses to gypsum of five peanut cultivars grown on Fuquay loamy sand at the Tifton location (Walker and Keisling, 1978)**

responses to the application of 615 kg gypsum ha^{-1} (550 lb ac^{-1}) on Fuquay and Tifton loamy sands but not on the Greenville sandy loam, all of which contained similar and adequate levels of Mehlich I soil test Ca. No significant differences in terms of the populations of *Pythium* and *Sclerotium rolfsii* were obtained. Later, Walker and Csinos (1980) studied the effect of gypsum on yield, quality, and incidence of pod rot in five peanut cultivars on two soils having different initial Mehlich I Ca levels. On the Greenville sandy loam soil (soil test Ca = 752 kg ha^{-1} = 670 lb ac^{-1}), no significant responses to gypsum applications were recorded nor was pod rot detected. The results obtained on the Stilson loamy sand (Mehlich I Ca = 356 kg ha^{-1} ≡ 317 lb ac^{-1}) at Tifton are presented in Table 3.9.

Table 3.9 Effect of gypsum rate on yield and value of five peanut cultivars grown at Tifton (Walker and Csinos, 1980)

Cultivar	Gypsum Rate (kg ha^{-1})							
	0		560 (500)[¶]		1120 (1000)		1680 (1500)	
	Yield kg ha^{-1}	Value $	Yield kg ha^{-1}	Value $	Yield kg ha^{-1}	Value $	Yield kg ha^{-1}	Value $
Florunner	4765a[†] (4242)	2290A	5684a (5060)	2735B	5621a (5004)	2734B	5682a (5059)	2791B
Tifrun	2935a (2613)	1281A	4757b (4235)	2028B	4763b (4240)	2164B	5004b (4455)	2209B
GA 194	2481a (2209)	1040A	4583b (4080)	2003B	5046c (4492)	2259C	5168c (4601)	2393C
Florigiant	3062a (2726)	1305A	5062b (4507)	2324B	5126b (4563)	2442B	5201b (4630)	2493B
Early Bunch	2509a (2233)	995A	4677b (4164)	2149BC	4952b (4409)	2337C	4945b (4402)	2400CD

† Means arranged horizontally followed by the same letter are not significantly different according to Duncan's Multiple Range Test (P = 0.05)
¶ Values in () are in lb ac^{-1}

Yield responses to gypsum rates in excess of 560 kg ha^{-1} (500 lb ac^{-1}) were only obtained with the GA 194 cultivar. The crop value for all cultivars was significantly increased by 560 kg gypsum ha^{-1} but for the GA 194 cultivar, the crop value increased with gypsum rate up to 1120 kg ha^{-1} (1000 lb ac^{-1}). Although pod rot incidence was not high, it was reduced significantly by gypsum application in all but the Florunner cultivar which had the lowest incidence.

Walker et al. (1981) obtained yield responses for Florunner peanuts to gypsum up to 445 kg ha^{-1} (400 lb ac^{-1}) on a Lakeland sand but no response on a Greenville sandy loam which had Mehlich I soil test Ca values of 254 and 643 kg ha^{-1} (226 and 572 lb ac^{-1}), respectively, prior to gypsum application. Alva et al. (1989) and Gascho and Alva (1990) demonstrated a yield and gross return advantage to the application of 224 kg Ca ha^{-1} (200 lb Ca ac^{-1}) (963 -1120 kg gypsum ha^{-1} depending on purity ≡ 850-I000 lb ac^{-1}) broadcast at first bloom of different gypsum materials on a Lakeland sand having an initial Mehlich I Ca = 127 kg ha^{-1} (113 lb ac^{-1}) but no response on a Tifton loamy sand with an initial Mehlich I Ca level of 665 kg ha^{-1} (592 lb ac^{-1}) (Table 3.10). This application rate is currently recommended for use in Georgia on Runner and Spanish type peanuts. In a subsequent experiment, Gascho and Alva (1990) found no significant yield advantage to doubling this recommended rate or splitting applications during the season on Runner or Virginia type peanuts grown on Lakeland sand under severe leaching conditions.

Gaines et al. (1989) demonstrated that yield responses in Florunner peanuts to 560 kg gypsum ha^{-1} (450 lb ac^{-1}) were possible provided that the Mehlich I Ca was below 540 kg ha^{-1} (480 lb ac^{-1}) but, in Virginia type peanuts, yield responses were even obtained when Mehlich I Ca was 1559 kg ha^{-1} (1388 lb ac^{-1}). Gaines et al. (1991) obtained significant yield and crop value responses to gypsum applications of up to 896 kg ha^{-1} (800 lb ac^{-1}) on Virginia NC-7 variety but not on Florunner which did not respond at all to gypsum even at a Mehlich I Ca level of 200 mg kg^{-1} (Table 3.11). There were no responses to gypsum in excess of 896 kg ha^{-1} (800 lb ac^{-1}). The lack or response to gypsum above 896 kg ha^{-1} (800 lb ac^{-1}) in NC-7 peanuts at any Mehlich I Ca level does not agree with their previous results.
In the most recent experiments, the greatest yield, grade, and value for Virginia type peanuts were attained only when gypsum at 1120 kg ha^{-1} (1000 lb ac^{-1}) was broadcast regardless of limestone application rate (Gascho et al., 1993b). In a series of uniform experiments at 9 locations with Runner and Virginia type peanuts, Gascho et al. (1993a) obtained responses only on Virginia type peanuts to gypsum at 1120 kg ha^{-1} (1000 lb ac^{-1}) applied at bloom even where the soil had received lime or gypsum at the same rate preplant on soils of low initial Mehlich I Ca level. As the level of Mehlich I Ca increased, the response weakened substantially (Table 3.12).

While there is some conflict in the data from Georgia, the overall picture is one of more frequent responses in large seeded peanuts (Virginia types) to gypsum up to rates of 860 lb ac^{-1} band placed over the row or 1720 lb ac^{-1} broadcast over the entire field.

3.1.6 State Recommendations for Peanuts

3.1.6.1 Gypsum

Before presenting the state gypsum recommendations, a brief recap of the essence of the experimentation which has been conducted will be presented as background. It is true to say that large- rather than small-seeded varieties generally show greater

Table 3.10 Florunner peanut yield and gross return responses to different gypsum materials at 224 kg Ca ha^{-1} (200 lb ac^{-1}) on two Georgia soils of different initial Mehlich I Ca content (Alva et al., 1989; Gascho and Alva, 1990)

Gypsum Material	Yield (kg ha^{-1})	SMK (%)	Gross Return[§] ($ ha^{-1})
Lakeland sand (Initial Ca = 127 kg ha^{-1})(113 lb ac^{-1})			
Crystalline	4480a[†] (3988)[¶]	70a	3134a [1269]·
Phosphogypsum	4387ab (3905)	69a	3019ab [1222]
Coarse powder	4107abc (3656)	68a	2812abc [1138]
Fine powder (dry)	3862abc (3438)	68a	2624abcd [1062]
Granular 1	3462abc (3082)	70a	2400bcd [971]
Granular 2	3302bc (2940)	68a	2116cd [857]
Pelleted	3100c (2760)	67a	2101d [851]
Control	3033c (2700)	61b	2033d [823]
Tifton loamy sand (Initial Ca = 665 kg ha^{-1})(592 lb ac^{-1})			
Crystalline	4415a (3931)	65a	3072a [1243]
Phosphogypsum	4395a (3913)	65a	3002a [1215]
Coarse powder	4272a (3803)	65a	2924a [1183]
Fine powder (dry)	4035a (3592)	65a	2777a [1124]
Granular 1	3983a (3546)	66a	2776a [1124]
Granular 2	4589a (4086)	66a	3217a [1302]
Pelleted	4333a (3858)	66a	2998a [1213]
Control	4651a (4141)	66a	3254a [1317]

† Means followed by the same letter for each soil are not significantly different at P = 0.05
§ For quota peanuts according to the USDA Peanut Loan Schedule, 1988
¶ Values in () are in lb ac^{-1}
· Values in [ ] are in $ ac^{-1}

Table 3.11 Effect of gypsum at different soil Ca levels on yield and value of two varieties of peanuts (Gaines et al., 1991)

Gypsum rate ($kg\ ha^{-1}$)	Soil Ca ($mg\ kg^{-1}$)	Pod Yield ($kg\ ha^{-1}$)		Value ($\$\ ha^{-1}$)	
		Florunner	NC-7	Florunner	NC-7
0	200	4890 (4354)†	2810 (2502)	3527 [1428]•	1818 [736]
448 (400)	218	5100 (4540)	4720 (4202)	3631 [1470]	3250 [1316]
896 (800)	258	4920 (4380)	5070 (4514)	3512 [1422]	3567 [1444]
1344 (1200)	248	4970 (4425)	5330 (4745)	3562 [1442]	3789 [1534]
0	682	4120 (3668)	4370 (3891)	2892 [1170]	2966 [1200]
448 (400)	762	4210 (3748)	4660 (4149)	3008 [1218]	3120 [1263]
896 (800)	736	4540 (4042)	5160 (4594)	3194 [1293]	3572 [1446]
1344 (1200)	734	3830 (3410)	4150 (3695)	2937 [1189]	2934 [1187]
$LSD_{0.05}$†		ns	410 (365)	ns	348 [141]

† Values in () are in $lb\ ac^{-1}$; • Values in [ ] are in $\$\ ac^{-1}$

responses to gypsum applications. Gypsum responses in all varieties are more common on soils testing low rather than high in soil Ca. Because, in the past, farmers have been diligent in following Cooperative Extension Service recommendations, the vast majority of soils on which peanuts are currently cultivated are likely to test high in soil Ca with lower requirements for gypsum.

The currently recommended gypsum rates for peanuts in the Southeastern States are presented in Table 3.13. Rates are presented for both band and broadcast applications but, these are essentially the same on a unit area basis as peanuts are planted in rows usually between 90 and 100 cm (35 and 39 in) apart. Thus, in all cases if correction is made for the area covered in a banded application, one arrives at the broadcast rate.

Table 3.12 Effect of various Ca sources applied preplant and gypsum (1120 kg ha^{-1}) applied at full bloom on yield of Runner and Virginia peanuts on soils of different intitial Mehlich I Ca level (Gascho et al., 1993a)

Ca Treatment		Bonifay sand	Bonifay sand	Lakeland sand
Preplant	Bloom	Initial Ca = 42 mg kg^{-1}	Initial Ca = 68 mg kg^{-1}	Initial Ca = 155 mg kg^{-1}
Runner type yield (kg ha^{-1})				
Calcite	Gypsum	2113 (1881)†	3315 (2951)	4792 (4266)
Calcite	No gypsum	1629 (1450)	3416 (3041)	5468 (4868)
Dolomite	Gypsum	2734 (2434)	3336 (2970)	5232 (4658)
Dolomite	No gypsum	2533 (2255)	3231 (2877)	5706 (5080)
Gypsum	Gypsum	1767 (1573)	2952 (2628)	3658 (3257)
Gypsum	No gypsum	1847 (1644)	2572 (2290)	4232 (3768)
Control	Gypsum	1353 (1205)	2305 (2052)	4062 (3616)
Control	No gypsum	1450 (1290)	2492 (2219)	3874 (3449)
Virginia type yield (kg ha^{-1})				
Calcite	Gypsum	2549 (2269)	3106 (2765)	6356 (5659)
Calcite	No gypsum	2024 (1802)	3580 (3187)	6048 (5384)
Dolomite	Gypsum	3169· (2821)	3213 (2860)	6146 (5472)
Dolomite	No gypsum	2211 (1968)	2560 (2279)	5928 (5278)
Gypsum	Gypsum	2676· (2382)	2534 (2256)	6280 (5591)
Gypsum	No gypsum	1851 (1648)	2645 (2355)	5598 (4984)
Control	Gypsum	2303· (2050)	2900· (2582)	6436· (5730)
Control	No gypsum	860 (766)	1515 (1348)	4428 (3942)

· Denotes a significant difference (1% level) between gypsum and no gypsum at bloom
† Values in () are in lb ac^{-1}

Table 3.13 Recommended gypsum rates for peanuts in the Southeast (Hodges et al., 1994)

State	Type	Soil Ca	Gypsum recommendation			
			lb ac^{-1}		kg ha^{-1}	
			Band†	Broadcast	Band	Broadcast
Alabama	Runner	Low	250•		280	
		Low	500		560	
		Med	250		280	
Florida	Virginia	All	800	1600	898	1795
	Runner, Spanish-seed	All	400	800	449	896
	Runner, Spanish	Low	400	800	449	896
Georgia§	Virginia	All	688-860	1376-1720	772-956	1544-1913
	Runner, Spanish-seed	All	344-430	688-860	386-483	772-965
	Runner, Spanish	Low	344-430	688-860	386-483	772-965
North Carolina	Virginia	All	600-800	1200-1600	673-897	1346-1795
South Carolina	Virginia	All	600-800	1200-1600	673-897	1346-1795
	Runner, Spanish	All	400-500	800-1000	449-561	898-1122
Virginia	Virginia, Seed	All	600	900-1500	673	1010-1683

† Band widths vary by State: Alabama = 30 cm (12 in); Florida, Georgia, North Carolina, South Carolina = 45 cm (18 in); Virginia = 50 cm (20 in)
§ Values for Georgia have been converted from Ca to equivalent pure $CaSO_4.2H_2O$
• When lime is applied

It is difficult to explain why there are such wide differences in rates of gypsum recommended by adjoining states. This could partly be due to the differences in the nature of the sites selected for experimentation in different states and partly due to a more conservative approach in some states than others. Nevertheless on a whole field basis (broadcast application), the maximum recommended rate of gypsum application to peanuts is 1913 kg ha^{-1} (1720 lb ac^{-1}) for Virginia type peanuts in Georgia which should be used as the starting value in the calculation of the risk of using phosphogypsum. Since peanuts are never cultivated as a monocrop but rather in rotations to control diseases, this value would become 957 and 638 kg ha^{-1} (850 and 570 lb ac^{-1}) for 2- and 3-year rotations, respectively, with peanuts appearing only once in that time (See Section 3.1.6.2).

3.1.6.2 Rotations

To calculate meaningful risk assessments for the use of phosphogypsum on peanuts, the cropping system must be taken into consideration. Unfortunately, it appears that this facet of peanut production was completely ignored by The Fertilizer Institute in its questionaire (Docket A-79-11) and consequently, was not taken into consideration by the EPA in the development of the Final Rule on phosphogypsum (Environmental Protection Agency, 1992). In all States in the Southeast, the Cooperative Extension Service (Gooden et al., 1991; Hartzog et al., 1990) recommends that peanuts be cultivated in a rotation with other crops which are not hosts for peanut pests, particularly, root-knot nematode (Meloidogyne arenaria) and white mold fungus *(Sclerotium rolfsi).* In fact, the National Peanut Council (Baldwin and Sullivan, 1989) in its Land Selection and Rotation Recommendations, states:

> *Peanuts should be grown in only one* year *out of three with crops that are resistant to nematodes, white mold and other diseases affecting peanuts. Recommended rotational crops include corn, sorghum, grass sods, small grains and cotton (especially where there is a nematode problem). Avoid other legumes and vegetable crops in a three year rotation that may build up nematodes and soil borne diseases.*

The benefits of rotating peanuts with cotton are clearly evident in Table 3.14. While the use of a nematicide certainly increases the yield and return, it is not nearly as effective as a rotation. Increasing the number of years in cotton in the rotation also has great benefit. Other crops such as bahiagrass *(Paspalum notatum)* and corn (Zea *mays)* are equally effective in controlling peanut pests and promoting yield but a legume such as soybeans is not as effective (Table 3.15) (Cope and Starling, 1994; Jacobi et al., 1994). The economic advantage in rotating peanuts with non-host crops ensures that very few farmers would ever be so foolish as to cultivate continuous peanuts as a monocrop. There is absolutely no senario where peanuts are likely to be cultivated on the same piece of land continuously for decades.

Table 3.14 Effect of peanut-cotton crop rotation on peanut yield, net return, and pest incidence in the last crop in the rotation (Rodriguez-Kabana, 1994)

Rotation	Yield in 1990 (lb ac^{-1})	Nematodes (# 100 cm^{-3})	White mold (# 100 m^{-1})	Net return from 1990 peanut crop ($ ac^{-1})	
				World price	US support price
No nematicide					
P-P-P-P-P-P[†]	1546	283	137	-136.72	-90.50
C-P-C-P-C-P	2235	128	110	53.65	105.05
C-C-P-C-C-P	2820	88	90	138.43	271.07
Nematicide					
P-P-P-P-P-P	2088	226	145	14.97	29.32
C-P-C-P-C-P	2712	59	100	105.42	206.43
C-C-P-C-C-P	3417	50	84	207.6	406.51
$LSD_{0.05}$	507	114	25		

[†] P = peanuts, C = cotton

Table 3.15 Effect of rotation length on peanut yield (Cope and Starling, 1994; Jacobi et al., 1994)

Rotation Length	Peanut Yield (lb ac^{-1})		
	Crop in Rotation		
	Corn	Soybean	Cotton
1 Year	3457	3360	3150
2 Year	3753	3553	3373
3 Year	4268	3684	4229

These results are reflected in the individual state recommendations for rotation peanuts which are summarized in Table 3.16. There is not a single state in the Southeast which does not recommend the rotation of peanuts with other crops for disease and pest control purposes.

Table 3.16 Official state recommendations for rotating peanuts

State	Official Recommendation	Source
Alabama	Rotate behind a non-legume crop every 2 or more years	Hartzog (1995)
Florida	Rotate behind a non-legume crop every 2-4 years	Whitty (1995)
Georgia	Plant peanuts in the same field once every 3 years or longer	Beasley (1995)
Mississippi	Rotate with grass crops, corn or cotton	Ruscoe (1995)
North Carolina	Rotate with grass crops or cotton	Sullivan (1995)
South Carolina	Do not plant peanuts in the same field more often than every 3rd to 4th year	Gooden (1995)
Tennessee	Rotate every 3 years with a non-legume	Rutledge (1995)
Texas	Plant peanuts in the same field once every 2 to 3 years	Lemon (1995)
Virginia		Swann (1995)

The extent to which these recommendations are implemented by farmers is indicated in Table 3.17. In fact, the greatest proportion of farmers (78% on average) cultivate peanuts in a 2- or 3-year rotation. Only a small proportion (10% on average), cultivate peanuts continuously on the same piece of land and most of that occurs in Alabama and Texas in which only 0-20% of the peanut land receives gypsum in any given year. Thus, very little land anywhere in the peanut belt is likely to receive any form of gypsum applications on a continuous basis every year for an extended period. In Alabama and Texas before phosphogypsum use was banned, only 0-20% of the gypsum use on peanuts was in the form of phosphogypsum (Hartzog, 1995; Lemon, 1995). Thus, over these two states very little land is likely to be contaminated by repeated applications of phosphogypsum.

Thus in arriving at the maximum rate of phosphogypsum likely to be applied to the same piece of land for an extended period of time, the state gypsum recommendation must be divided by the length of the rotation in which peanuts appear. This factor clearly lies on average between 2 and 3.

Table 3.17 Proportion of peanut land in various rotation systems

State	Percentage of land in rotation type				
	Continuous[†]	2-year	3-year	Longer	Source
Alabama	20	45	20	15	Hartzog (1995)
Florida	0	30	30	30	Whitty (1995)
Georgia	5	27	33	35	Beasley (1995)
Mississippi	0	80	20	0	Ruscoe (1995)
North Carolina	2	54	35	9	Sullivan (1995)
South Carolina	0	25	60	15	Gooden (1995)
Tennessee	0	0	100	0	Rutledge (1995)
Texas	40	30	30	0	Lemon (1995)
Virginia	5	65	25	5	Swann (1995)

[†] Peanuts following peanuts for 2 or more consecutive seasons but rarely for more than 3 seasons

3.2 Tomatoes

Raleigh and Chucka (1944) who investigated the causes of blossom-end rot in tomatoes found that any nutrient variable which resulted in production of fruit with less than 0.2% Ca, increased the incidence of the disorder. Evans and Troxler (1953), working in North Carolina, obtained reductions in blossom-end rot in tomatoes on a Faison fine sandy loam soil when a combination of gypsum applied to the soil at 2700 lb ac^{-1} and leaf sprays of $CaCl_2$ were used (Table 3.18). Although the Ca treatments substantially increased the yields, significance at the 5% level was not reached.

Table 3.18 Effect of calcium treatments on yield and blossom-end rot in tomatoes (Evans and Troxler, 1953)

Treatment (lb ac^{-1})	Yield (bu ac^{-1})	No. fruits harvested	Frequency of blossom-end rot (%)
Control	178	529	17.7
1400 Gypsum	198	566	16.1
2700 Gypsum + $CaCl_2$ spray	257	625	13.1
$LSD_{0.05}$	ns[†]	ns	2.9

[†] ns = non significant

Geraldson (1956) substantially reduced the incidence of blossom-end rot in tomatoes on a Leon fine sand by applying 2000 lb gypsum ac^{-1} in 4 gallon crocks in the greenhouse and found that the ratio of Ca to total soil solution salts measured by electrical conductivity was a good indicator of the soil conditions under which the disease could be expected (Table 3.19).

Table 3.19 Effect of gypsum application on incidence of blossom-end rot in tomatoes and associated soil solution parameters (Geraldson, 1956)

Treatment	Soil solution composition			Blossom-end rot
lb ac^{-1}	Total SSS † ppm	Ca ppm	Ca/SSS	%
Control	2600	340	13.1	25.0
2000 Gypsum	3400	748	22.0	2.3

† Total soil solution salts

In a separate study involving the monitoring of commercial fields receiving different Ca applications, he found that, when $Ca(NO_3)_2$, $CaCl_2$ and $Ca(OH)_2$ were either applied on the soil or sprayed on to the plants, the incidence of blossom-end rot was markedly reduced which resulted in a greater proportion of marketable fruit (Table 3.20). Foliage sprays are clearly much more effective and more economical than soil applications of soluble Ca materials in controlling blossom-end rot.

Table 3.20 Effect of soluble Ca salts applied to the soil or as a foliage spray on the incidence of blossom-end rot in commercial tomato fields in Florida (Geraldson, 1956)

Treatment	Number of blossom-end rotted fruits per 40 ft row			
	Field 1 (staked)	Field 2 (unstaked)	Field 3 (staked)	Total
Control	71	146	88	305
500 lb $Ca(NO_3)_2$ ac^{-1} on soil	20	16	24	60
250 lb $CaCl_2$ ac^{-1} on soil	24	36	48	108
$CaCl_2$ spray	8	8	2	18
$CaCl_2/Ca(OH)_2$ spray	2	4	0	6
$LSD_{0.01}$				68.5

When the soil is initially acid, substantial yield responses of tomatoes have been obtained to the application of various types of limestone (Forsee and Hayslip, 1947; Forsee et al., 1951; Hortenstine and Stall, 1962) but unfortunately, it is impossible to separate the effects of acid neutralization from the contribution of Ca in such experiments.

Thus, there is scant field evidence that supports the use of gypsum for blossom end rot in tomatoes because leaf sprays are more effective.

3.3 Other Crops

Anderson (1968) obtained significant depressive effects of gypsum on Valencia oranges at rates of 1 and 2 t ac^{-1} despite the fact that leaf Ca and S were greatly increased (Table 3.21). However the high rates of gypsum severely reduced leaf Mg and K which may have been responsible for the decrease in yield.

In north Florida on an Ellzey fine sandy soil, Locascio et al. (1992) obtained a significant yield response in marketable potatoes to the application of 450 kg gypsum ha^{-1} (400 lb ac^{-1}) in one out of three seasons.

Table 3.21 Effects of agricultural grade gypsum and limestone on fruit yields and leaf composition of Valencia orange trees (Anderson, 1968)

Parameter	Treatments (t ac^{-1} y^{-1})				
	Gypsum				Limestone
	0	0.5	1	2	1
Yield (box $tree^{-1}$)	3.1a[†]	2.9ab	2.4bc	2.1c	3.0ab
Leaf Ca %	2.69a	3.09a	3.65b	3.90b	3.09a
Leaf Mg %	0.53a	0.39c	0.35d	0.30e	0.45b
Leaf K%	0.91a	0.88ab	0.80bc	0.78c	0.91a
Leaf S %	0.27a	0.45b	0.58c	0.70d	0.27a

[†] Within a given row, data followed by the same letter do not differ at a probability level of 0.05

3.4 State Calcium Recommendations for Crops Other than Peanuts

A summary of the current Cooperative Extension Service recommended rates for Ca use on other crops is presented in Table 3.22. Thus, the maximum annual recommended Ca application rate for use on crops other than peanuts is 200 lb Ca ac which is equivalent to 860 lb gypsum ac^{-1} (965 kg ha^{-1}).

Table 3.22 State Ca recommendations for other crops

State	Crop	Ca rate (lb ac^{-1})	*Source*
Alabama	All	No recommendation	Adams et al. (1994)
Florida	All	No soil recommendation Foliar spray	Koo (1984), Hanlon et al. (1990), Hochmuth and Hanlon (1989)
Georgia	Peppers, tomatoes	100-200	Plank (1989)
Georgia	Apples	Spray	Plank (1989)
North Carolina	All	No recommendation	Tucker and Rhodes (1987)
South Carolina	Apples	Spray	Anon (1982)
Tennessee	Peppers, tomatoes	100	Savoy et al. (1991)
Virginia	All	No recommendation	Donohue and Hawkins (1979)

4. SULFUR REQUIREMENTS OF CROPS

Sulfur has frequently been found to be a nutrient limiting the yields of many crops in the Southeast. Crops take up between 10 and 20 lb S ac^{-1} for normal growth (Jordan, 1964). In early times, the main source of phosphorus (P) for crops was single superphosphate which contains levels of S that were sometimes adequate for many crops when this source of P was applied to soils. In addition, ammonium sulfate was often the main N source. With the advent of triple superphosphate and mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP) which contain minimal amounts of S, and the increasing use of urea and ammonium nitrate instead of ammonium sulfate as N sources, the incidence of S deficiency in crops began to reappear. In fact, the total S content of fertilizers purchased in the Southeast declined from 514,800 to 183,000 short tons over the period 1949/50 to 1972/73 (Beaton et al., 1974).

Subsequently, with the increased levels of S in atmospheric precipitation from the burning of fossil fuels, S requirements of crops in certain areas where fallout was high were satisfied and deficiencies disappeared again. For example, in Florida during the period 1955 to 1980, the average SO_4 concentration in rainfall increased by a factor 1.6 resulting in the deposition of approximately 7-11 kg S ha^{-1} (6-10 lb ac^{-1}) in 1980 (Brezonik et al., 1980). In South Carolina, the total S added to soil from the atmosphere increased from 11.2 kg ha^{-1} yr^{-1} (10 lb ac^{-1}yr^{-1} in 1973 to 20 kg ha^{-1}yr^{-1} (18 lb ac^{-1}yr^{-1}) in 1976/77 (Jones et al., 1979). In Georgia, the average value was 18.8 kg S ha^{-1}yr^{-1} (17 lb ac^{-1}yr^{-1}) for the period 1964-75 (Giddens, 1975). More recently as a result of the Clean Air Act, S deposition from the atmosphere will most probably decrease with time and the likelihood of S deficiencies reappearing again will increase. In support of this, Suarez and Jones (1982) found that by 1980 total S added to soil in South Carolina had decreased to 10 kg S ha^{-1} (9 lbac^{-1}).

A further complicating factor arises from the ability of many subsoils to retain significant quantities of exchangeable SO_4 which can be available for uptake (Kamprath et al., 1956a). As a consequence, crop responses to S have been somewhat cyclic and erratic in nature, depending on type of fertilizer used, soil type, and S additions from the atmosphere making the chances of predicting a response to S from a soil analysis of extractable SO_4 somewhat low. In addition, there is a strong interaction between N and S. In other words, the response to S depends on the level of N. Figure 4.1 shows that a response to S was only obtained after the level of fertilizer N had been increased.

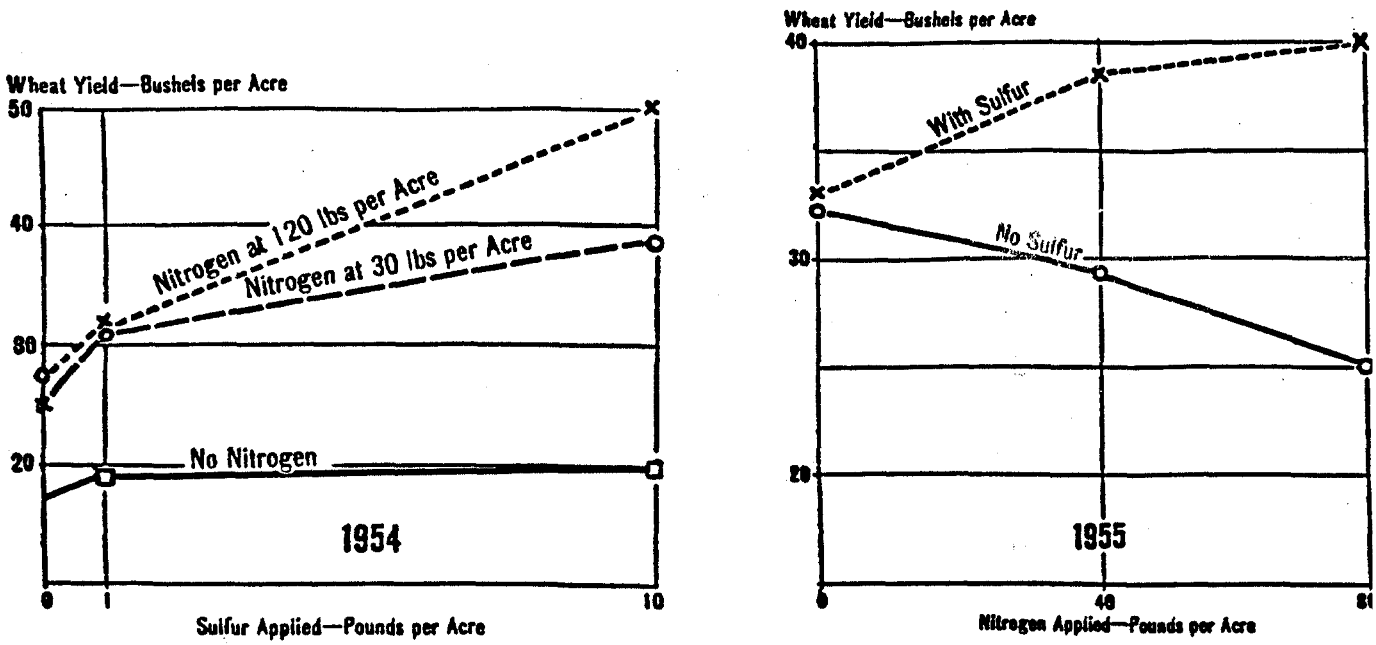

Figure 4.1 Interaction between N and S for wheat (Jordan and Reisenauer, 1957)

4.1 Florida

The data of Blaser et al. (1941) hinted that responses to S were likely in Florida. Some of the earliest actually recorded responses to S were obtained on cotton by Harris et al.

(1945) who showed that this condition was widespread in the state and that the amounts of S applied in rainfall and fertilizer were generally insufficient to meet crop needs. Bledsoe and Blaser (1946) suspected that some of the responses obtained to single superphosphate were due to its S content which was substantiated by their results in Table 4.1. When pure phosphoric acid was used as the P source, a large response to added S was obtained whereas when single superphosphate was used to supply P, the S needs of the crop were also largely met by the S from the fertilizer.

Table 4.1 Response of red clover to S fertilization with different sources of P (Bledsoe and Blaser, 1946)

Source of phosphorus	Yield of red clover (lb ac^{-1})	
	No Sulfur	Sulfur (60 lb ac^{-1})†
Single superphosphate (8-10% S)	337	383
85% Phosphoric acid (0% S)	31	245

† Equivalent to 322 lb pure gypsum ac^{-1}

Subsequently, Neller et al. (1951a & b) demonstrated that the S content of superphosphate when applied at 350 lb ac^{-1} every year (≡ 28-35 lb S ac^{-1} or 150-190 lb gypsum ac^{-1}) was sufficient to meet the S needs of various pastures in Florida (Table 4.2). Gypsum at 175 lb ac^{-1} (32 lb S ac^{-1}) as an additive to calcined phosphate which contains no S, was sufficient to meet the crop requirements for S as measured by tissue analyses.

Table 4.2 Effect of gypsum applications on growth of pastures fertilized with two different P sources (Neller et al., 1951a & b)

Treatment	Yield (lb ac^{-1})		
	Clover-Bahiagrass	White clover	Carpet grass
Superphosphate every 2 years	2064		
Superphosphate every year	3357	202	2789
Calcined phosphate plus 175 lb gypsum† ac^{-1}	3849	194	2427
$LSD_{0.05}$	706		376

† Equal to the gypsum contained in the superphosphate

Neller (1952) showed that the omission of gypsum to furnish S in the fertilizer program on sandy flatwood soils of peninsular Florida resulted in almost complete failure of White Dutch clover. The summer growth of the associated grass in the pasture was greater with a higher protein content on areas where the clover grew in the winter due to proper S fertilization. On a range of field crops, Harris et al. (1954) indicated that there was a suggestion in some of their results that sulfur might be required but the differences were not significant. Neller (1959b) subsequently demonstrated that there was very little SO_4-S in the surface horizons of sandy Florida soils but considerable amounts were present in many of the subsurface layers where the increased clay content appeared to retain the SO_4-S. The source of much of this SO_4-S was thought to be from the annual deposition of about 5 lb S ac^{-1} in rainfall. Thompson and Neller (1963) obtained forage yield responses to gypsum application on a virgin Orangeburg loamy sand which contained very little SO_4-S in the top 18 in of soil, but no response on a Carnegie fine sandy loam which contained substantial levels of SO_4-S below 6 in (Table 4.3). They indicated that soils where subsoil S was close to the surface, may need S fertilizer at planting. Crops were unlikely to respond further once the roots had penetrated the subsoils where the S content was higher. On the other hand on deep sandy soils where the reserves of S were much deeper, crops would be likely to require S fertilizer additions to the topsoil for the entire cropping season to meet their requirements, adequately.

Table 4.3 Effect of gypsum on yield of forages on two Florida soils fertilized with a complete fertilizer (Thompson and Neller, 1963)

Gypsum rate (lb ac^{-1})	Tissue S (%)	Yield of air-dry forage (lb ac^{-1})		
		1954	1955	1956
Orangeburg loamy sand (Crimson clover)				
0	0.139	1871	1533	2567
22	0.147	2192	1774	3113
44	0.148	2244	1788	3130
88	0.158	2272	1997	3647
176	0.179	2331	2011	3461
$LSD_{0.05}$	0.021	275	225	488
Carnegie fine sandy loam (Coastal bermudagrass, red, crimson and Ladino clover)				
0	0.151	900	3300	5260
22	0.171	1100	3450	4814
44	0.190	1007	3520	5841
88	0.196	820	3600	4772
176	0.242	861	3300	5353
$LSD_{0.05}$	0.022	ns†	ns	ns

† ns = non significant

In a greenhouse experiment with citrus plants on four Spodosols, Martin et al. (1988) obtained improved fibrous root development with gypsum treatments up to 2240 kg ha^{-1} (2000 lb ac^{-1}) with commercial mined gypsum being superior to phosphogypsum. However, Lin et al. (1988) studying citrus fibrous root development in a spodic soil horizon in the greenhouse found that phosphogypsum had no significant effect. In field experiments at two flatwood sites, Smith et al. (1989) obtained a response in trunk diameter of Valencia orange trees at one location as a result of deep soil disturbance but phosphogypsum incorporation at 5000 kg ha^{-1} (4450 lb ac^{-1}) did not further increase tree growth at either site.

Jordan (1964) found that bermudagrass and clover did not respond to S applications on a Ruston fine sandy loam in which S levels increased with depth but on an Orangeburg loamy fine sand with minimal subsoil S, significant crimson clover responses were obtained (Table 4.4). On the other hand, over a 7 year perior, corn did not respond to S applications on the latter soil.

Mitchell and Gallaher (1979) found that while corn seedlings showed marked S deficiency symptoms early in the season, no significant yield responses to 10 kg S ha^{-1} (9 lb S ac^{-1} or 48 lb gypsum ac^{-1}) were obtained at the end of the season on an Arredondo fine sand probably due to the extraction of SO_4-S from subsoil horizons as the seedlings developed. Mitchell and Blue (1981 b) characterized the S fertility status of Florida Spodosols, Entisols, and Ultisols showing the distribution of SO_4-S with depth in the profile (Table 4.5). Clearly only the Ultisol order which is characterized by an increase in clay content with depth, retains sufficient SO_4-S to supply the needs of crops. The very sandy Spodosol and Entisol Orders retain very small amounts which are far below the requirements for many crops (Mitchell and Blue, 1981 a).

Table 4.4 Effect of rates of sulfur on yield of forages at two locations (Jordan, 1964)

Sulfur rate (lb ac^{-1})	Bermudagrass Yield at Jay (lb ac^{-1})			Crimson Clover Yield at Quincy (lb ac^{-1})		
	1954	1955	1956	1954	1955	1956
0	2079	3300	5260	1871	1533	2619
4 (21)†	2519	3540	4814	2192	1774	3113
8 (43)	2276	3520	5841	2244	1788	3130
16 (86)	1845	3600	4772	2272	1997	3647
32 (172)	1935	3300	5353	2331	2011	3461

† Gypsum equivalent

Table 4.5 Mean distribution of sulfate-S in the profiles of three soil orders in Florida (Mitchell and Blue, 1981b)

Horizon number from surface	SO_4-S (μg g^{-1})		
	Spodosols	Entisols	Ultisols
1	4±2	3±2	5±4
2	2±0	4±2	2±2
3	2±1	6±3	2±2
4	1±1	8±2	15±12
5	3±2	6±2	40±29
6	2±1	6±5	40±35
7	3±2	4±3	23±28

Mitchell and Blue (1989) found that when pasture is fertilized at low rates of N, S responses may not be observed in the first 4 years. However at higher rates of N fertilization, between 30 and 45 kg S ha^{-1} (27 and 40 lb S ac^{-1} ≡ 145 and 215 lb gypsum ac^{-1}) are needed annually to sustain yields of bahiagrass. Rechcigl (1989) and Rechcigl et al. (1989) increased the dry matter production of bahiagrass by 25% and also the crude protein content and digestability by applying 86 kg S ha^{-1} (75 lb S ac^{-1} ≡ 403 lb gypsum ac^{-1}) on a sandy soil. Myhre et al. (1990) increased citrus yields and juice quality by applying up to 1120 kg phosphogypsum ha^{-1} (1000 lb ac^{-1}) on a Myakka sand. Even greater improvements in juice quality were obtained on Oldsmar sand. Hunter (1989) conducted an extensive series of field trials on various crops (potato, cantaloupe, bell peppers, and sweet corn) at a number of sites to evaluate phosphogypsum as a Ca and S source. A summary of their results is presented in Table 4.6. Very few significant yield responses at the 5% level were obtained to gypsum applications, but the authors pointed out that because of the high value of these crops, economic returns could be expected with yield increases of as little 2-10%. This raises the question whether a lower level of statistical significance should be considered. At a 10% significance level, yield responses would also have been recorded on potatoes in 1986. The data from these experiments show a high degree of variability and should be regarded with some suspicion. Despite the trends in the data, if statistical significance is not reached, the differences are not real. In an experiment with citrus, they obtained a significant yield increase to an application of 1000 lb phosphogypsum ac^{-1}. In any event if these responses are real, it is unlikely that they arise soley from improved S and/or Ca nutrition of the crops involved. While their data were not conclusive, they stated that there was no significant effect of phosphogypsum on the radiation levels found in these crops.

Table 4.6 Effect of gypsum rates on the relative yields of a number of crops grown on sandy soils in Florida (Hunter, 1989)

Gypsum rate lb ac^{-1}	Crop yield					
	Potato		Cantaloupe	Bell pepper	Sweet corn	
	1986	1987	1987	1987	Site 1	Site 2
0	100.0a[†]	100.0a	100.0a	100.0a	100.0a	100.0a
500				143.9a	119.5ab	122.2a
500 Band						172.2b
1000	104.8a	97.3a		123.4a	140.6bc	122.2a
1500			117.3a			
2000	122.6a	108.5a		138.4a	155.1c	
3000			142.0a		139.5bc	

[†] Values in a column followed by the same letter are not significantly different at the 5% level

Most of the data on Florida crops shows that responses to gypsum applications are likely to be observed at rates up to 500 lb gypsum ac^{-1} yr^{-1}, discounting the data of Hunter (1989), the validity of which is open to question.

4.2 Other States

Probably the earliest recorded response to S was obtained in Arkansas on cotton by Younge (1941) on 10 Coastal Plain soils. He applied 12 lb S ac^{-1} (≡ 64 lb gypsum ac^{-1}) and obtained a significant mean response of 44 lb lint cotton ac^{-1} due largely to an increase in the rate of growth and the number of bolls produced. With the advent of high analysis P fertilizers which contain no gypsum, Volk et al. (1945) in Alabama concluded that deficiencies of secondary nutrients such as S were likely to arise. They obtained substantial yield responses of seed cotton (double) to 400 lb gypsum ac^{-1}. Neas (1953) observed a S deficiency in tobacco when sulfate was omitted from the fertilizer. With similar concerns in North Carolina, Kamprath et al. (1956b) obtained responses to S in a field experiment with rates of 0, 4, 8, 16 and 32 lb S ac^{-1} (≡ 0, 21, 43, 86, 172 lb gypsum ac^{-1}) on cotton and tobacco early in the season but only on cotton were these sustained at the end of the season. This probably resulted from the extraction of S from SO_4 stored in the lower part of the profile where clay content increases (Neller, 1959a). Jordan and Bardsley (1958) obtained significant yield responses (260 lb seed cotton ac^{-1}; 504 lb clover hay ac^{-1}; 396 lb clover-grass hay ac^{-1}; 261 lb leaf tobacco ac^{-1}) when S was applied at rates of 0, 4, 8, 16 and 32 lb S ac^{-1} (≡ 0, 21, 43, 86, 172 lb gypsum ac^{-1}) at various locations in the Southeast with corresponding increases in tissue S contents. In Alabama, Jordan and Ensminger (1958) reported a 16% average increase in seed cotton yields over 12 locations on treatments receiving S containing fertilizers relative to S free treatments. Anderson and Webster (1959) obtained no response to S applications (0 to 32 lb S ac^{-1}= 0 to 172 lb gypsum ac^{-1}) on a Leadvale silt loam for the first 5 years of cultivation to cotton because of a high SO_4 content in the upper 12 in of soil whereas, on a Norfolk loamy sand which only contained 1 ppm of extractable S in the topsoil but substantial reserves in the subsoil, response to S was obtained in the fifth year. On the other hand, Pedersen (1959) found no yield response in corn to S at rates up to 32 lb ac^{-1} (172 lb gypsum ac^{-1}) in Alabama. In a regional study in the Southeast, Jordan (1964) reported responses to S applications on 63% of the sites tested. A summary of these results is presented in Table 4.7.

Fox et al. (1964) who applied gypsum at rates of 0, 10, 20 and 40 lb S ac^{-1} (54, 108, 215 lb gypsum ac^{-1}) on sandy soils in Nebraska similar to those in the Southeast obtained yield responses in alfalfa and corn.

Martin and Walker (1966) summarized the results obtained in the Western States showing that S deficiency was widespread and that yield responses to gypsum applications up to 80 lb S ac^{-1} (430 lb gypsum ac^{-1}) were common in states such as

California, Oregon, and Washington. Similar responses were reported by Stewart and Whitfield (1965) in Colorado. Jones and Ruckman (1966) demonstrated that gypsum at a rate of 40 lb S ac^{-1} (215 lb gypsum ac^{-1}) was sufficient to supply the needs of grassland in California. These data conflict with the statement in the EPA's response to the TFI objection (Page 4 of this Report), namely,

> *Although the data from California show much higher application rates than those for peanuts, we do not believe that California's rates are necessarily associated with reclamation.*

There can be little doubt that the rates quoted in Docket A-79-11 Page 2, Question2, Items 1-8 which range from 1-2 t ac^{-1} are reclamation rates and not rates used to supply S as a nutrient which would be of the order of 200-400 lb gypsum ac^{-1}.

In Georgia, Anderson and Futral (1966) found that cotton was the crop that responded best to applications of S at rates up to 18 lb S ac^{-1} (97 lb gypsum ac^{-1}) and that the source of S (gypsum vs Na_2SO_4) had no effect. Their results also demonstrated that

Table 4.7 **Summary of yield responses (lb ac^{-1}) and tissue S levels (%) to S applications in the Southeast (Jordan, 1964)**

Location	Crop	Sulfur rates (lb ac^{-1})									
		0		4		8		16		32	
		Yield[¶]	Tissue S (%)	Yield	Tissue S (%)	Yield	Tissue S (%)	Yield	Tissue S (%)	Yield	Tissue S (%)
Calhoun, GA	Cotton	1172	0.75	1162	0.69	1134	0.69	1180	0.75	1121	0.80
Midville, GA	Cotton[†]	934	0.34	1157	0.31	1282	0.42	1344	0.45	1438	0.58
Watkinsville, GA	Cotton[†]	1569	0.33	1676	0.36	1707	0.43	1865	0.45	1829	0.60
Fleming, GA	Clover & bahiagrass[†]	1225	0.19	1570	0.20	1571	0.20	1523	0.21	1631	0.23
Summerville, SC	Clover and carpetgrass[†]	1750	0.19	1670	0.21	1830	0.22	1740	0.24	2320	0.27
Rock Mount, NC	Corn	69		70		64		68		63	
State College, MS	Cabbage	1337		1428		1276		1481		1255	
State College, MS	Turnips	3217		3820		3216		3451		3250	
Oxford, NC	Tobacco[†]	2055		2282		2326		2332		2323	
Rocky Mount, NC	Soybeans	1020		1170		1098		1296		1029	

[†] Significant yield responses at P = 0.05 were obtained at these locations
[¶] Yields for all crops except corn are in lb ac^{-1}. For corn, the yields are in bu ac^{-1}.

annual applications were necessary and that band placement of S sources was more efficient. In North Carolina on a Eustis sand, Woodhouse (1969) found that gypsum applied at between 28 and 56 kg S ha^{-1} (25 and 50 lb S ac^{-1} ≡ 134 and 268 lb gypsum ac^{-1}) significantly increased the yield of coastal bermudagrass in 7 out of 8 years. Daigger and Fox (1971) obtained yield increases to 66 kg S ha^{-1} (60 lb S ac^{-1} ≡ 322 lb gypsum ac^{-1}) in sweet corn only at low rates of N on a fine sandy loam in Nebraska. Increased root proliferation at the higher N rates probably made additional S from the subsoil available to the plants. Matocha (1971), working in Texas on coastal bermudagrass on a Troup loamy fine sand, obtained responses to gypsum at a rate of 50 kg S ha^{-1} (45 lb S ac^{-1} = 242 lb gypsum ac^{-1}). In North Carolina, Rhue and Kamprath (1973) showed that application of gypsum at a rate of 56 kg S ha^{-1} (50 lb S ac^{-1} ≡ 269 lb gypsum ac^{-1}) was readily leached from a Wagram loamy sand indicating that to sustain responses to gypsum, applications would have to be made annually on very sandy soils with no subsoil reserves. In Texas, Landua et al. (1973) demonstrated marked responses in coastal bermudagrass to 64 kg S ha^{-1} (57 lb S ac^{-1} ≡ 306 lb gypsum ac^{-1}) on Lakeland and Troup loamy fine sands. On sandy soils in Oklahoma similar to those in the Southeast, Bremer (1975) failed to obtain consistent yield responses to gypsum applied at a rate of 100 kg S ha^{-1} (89 lb S ac^{-1} ≡ 478 lb gypsum ac^{-1}) on bermudagrass and sorghum over a period of two years. In North Carolina, Rabuffetti and Kamprath (1977) found that responses of corn to gypsum at rates between 0 and 66 kg S ha^{-1} (59 lb S ac^{-1} ≡ 317 lb gypsum ac^{-1}) depended on the rate of N applied being greatest at high N rates. Similar NxS interactions have been reported by Stewart and Porter (1969) for corn, wheat and snapbeans.

In Louisiana, Golden (1979) obtained yield responses in sugarcane to gypsum at the rate of 24 lb S ac^{-1} (130 lb gypsum ac^{-1}) at 36 out of 38 locations where experiments were conducted. Because of the increasing levels of S applied to soil as atmospheric fallout during the period 1973-77, very few yield responses to S applied a rate of 18 kg ha^{-1} (16 lb S ac^{-1} ≡ 86 lb gypsum ac^{-1}) were obtained in South Carolina for a number of crops (Jones et al., 1979) (Table 4.8). Significance in the few cases where responses were obtained was only reached at the 10% level. In South Carolina, Matheny and Hunt (1981) found no significant improvement in the yield of soybeans as a result of applying 44.8 kg S ha^{-1} (40 lb S ac^{-1} = 215 lb gypsum ac^{-1}) as gypsum to a Norfolk loamy sand. Day and Parker (1982) in Georgia found no significant responses to the application of up to 112 kg S ha^{-1} (100 lb S ac^{-1} ≡ 538 lb gypsum ac^{-1}) to corn and soybeans during a 3-year period on sandy Coastal Plain soils. However at high rates of N, responses to S were obtained with bermudagrass (Table 4.9).

Golden (1983) obtained significant sugarcane yield responses (11%) to the application of 1 t phosphogypsum ac^{-1} (890 lb ac^{-1}) on fine textured soils along the Mississippi River while Sedberry et al. (1982) obtained no responses to the application of gypsum

Table 4.8 **Crop responses to 18 kg S ha^{-1} (16 lb S ac^{-1} ≡ 86 lb gypsum ac^{-1}) in South Carolina, 1974-78 (Jones et al., 1979)**

Crop	Yield unit	Sites	Yield	
			Without S	With S
Barley	ton ha^{-1} (t ac^{-1})	3	4.10 (1.82)	3.84 (1.71)
Field corn	ton ha^{-1} (t ac^{-1})	4	4.02 (1.79)	4.61* (2.05)
Silage corn	ton ha^{-1} (t ac^{-1})	1	8.05 (3.58)	8.86* (3.94)
Sweet corn	crates ha^{-1} (crates ac^{-1})	1	16.22 (6.57)	16.72 (6.77)
Cucumber	$100 ha^{-1} ($100 ac^{-1})	1	16.13 (6.53)	15.34 (6.21)
Snapbean	ton ha^{-1} (t ac^{-1})	3	2.70 (1.20)	2.51 (1.12)
Soybean	ton ha^{-1} (t ac^{-1})	1	2.55 (1.14)	2.51 (1.12)
Tomato	ton ha^{-1} (t ac^{-1})	3	13.21 (5.88)	13.44 (5.98)
Turnip	ton ha^{-1} (t ac^{-1})	3	23.40 (10.41)	26.30 (11.71)

* Significantly different at the 10% level

Table 4.9 **Effect of N and S treatments on yield of coastal bermudagrass over a 3 year period (Day and Parker, 1982)**

S Rate (kg ha^{-1})	Dry forage yield (kg ha^{-1})				
	N Rate (kg ha^{-1})				
	84 (75)†	168 (150)	336 (300)	672 (600)	Mean
0	5701a* (5076)	9405a (8373)	14378b (12800)	17768b (15819)	11813b (10517)
28 (25)	5517a (4912)	9394a (8363)	14856ab (13226)	18440a (16417)	12052ab (10730)
56 (50)	5820a (5182)	9809a (8733)	14772ab (13151)	18573a (16536)	12244a (10901)
112 (100)	5966a (5312)	9582a (8531)	15174a (13508)	18108ab (16121)	12208a (10868)

* Values followed by the same letter are not significant at the 5% level

† Values in () are in lb ac^{-1}

at rates up to 2 t ac^{-1} to soybeans on a Severn very fine sandy loam in Louisana. In Virginia, Reneau and Hawkins (1980) and Reneau (1983) obtained yield responses for both corn and soybeans to S applications up to 44 kg ha^{-1} (40 lb S ac^{-1} ≡ 215 lb gypsum ac^{-1}) on moderately well to well drained Coastal Plain soils with low extractable soil S (< 6-7 kg ha^{-1}) (5-6 lb ac^{-1}) (Table 4.10). Reneau (1983) showed that between 18 and 28 kg S ha^{-1} (16 and 25 lb S ac^{-1} ≡ 86 and 134 lb gypsum ac^{-1}) were required to achieve 90% of the maximum yield.

Table 4.10 Effect of S rates on yields of corn and soybeans in Virginia (Reneau and Hawkins, 1980; Reneau, 1983)

Crop	Soil	S Rate (kg ha^{-1})		
		0	22 (20)†	44 (40)
		Grain yield (kg ha^{-1})		
Corn	Slagel sandy loam	8260b• (7354)	9560ab (8511)	10410a (9268)
	Lakeland fine sand	7740b (6891)	8790a (7826)	8870a (7897)
	Dothan sandy loam	5900b (5253)	6200a (5520)	6800a (6054)
	Tatum silt loam	3600b (3205)	4500a (4006)	5500a (4897)
	Groseclose	11400b (10149)	11640b (10363)	12130a (10799)
Soybean	Dragston fine sandy loam	1980b (1763)	2320a (2065)	2340a (2083)

• Values in a row followed by the same letter are not significantly different at the 5% level
† Values in () are in lb ac^{-1}

In Alabama, Cope (1984) obtained a number of responses to S applied at a rate of 30 lb ac^{-1} (161 lb gypsum ac^{-1}) (Table 4.11). In Arkansas on a Roxana sandy loam, Wells et al. (1986) applied S to S deficient wheat at the tillering stage of growth and obtained a large and significant yield response from 15.3 to 44.4 bu ac^{-1} to the first 5 lb S ac^{-1} (27 lb gypsum ac^{-1}) with no further response being recorded up to an application rate of 40 lb S ac^{-1} (215 lb gypsum ac^{-1}).

Kamprath and Jones (1986) summarized the recent responses to the application of S to various crops in the Southeast (Table 4.12). On average less than half the sites showed responses to S. This reflects that substantial amounts of S are being applied to crops by atmospheric fallout, from subsoil reserves or in irrigation water.

Table 4.11 Percentage yield of treatments not receiving S since 1977 relative to treatments receiving 30 lb S ac^{-1} (161 lb gypsum ac^{-1}) in long term fertilizer experiments in Alabama (Cope, 1984)

Soil	Relative Crop Yield without S			
	Peanuts (1982)	Soybean (79-82)	Corn (79-81)	Sorghum (1982)
Hartsell fsl		90*	82*	87
Benndale fsl		97	101	96
Dothan fsl	100	88*	86*	89*
Lucedale fsl		95	84*	94
Lucedale scl		97	91	100
Dewey sil		94	95	88

* Yields significantly lower than for treatments receiving S at the 5% level

Table 4.12 Number of sites where responses to S fertilization were obtained in the Southeast (Kamprath and Jones, 1986)

Crop	Total # of Sites	# of Sites responding to S
Corn	11	6
Soybeans	9	2
Forage	6	3
Sugarcane	6	1
Vegetables	6	1
Small grain	3	2
Tobacco	3	1

Working with Granex onions in Georgia, Smittle (1986) obtained a significant response to 600 lb gypsum ac^{-1} in one out of two years on a Tifton loamy sand. Buttrey et al. (1987) obtained a 7% increase in corn forage yield on a Shelocta soil in the Ridge and Valley region of Southwest Virgina to the application of 67.2 kg S ha^{-1} (60 lb S ac^{-1} ≡ 323 lb gypsum ac^{-1}). Hern et al. (1988) obtained minimal and inconsistent increases in Ladino white clover yield on a well drained Lily silt loam in West Virginia to the application of S at 25 and 50 kg ha^{-1} (22 and 44 lb S ac^{-1} ≡ 118 and 236 lb gypsum ac^{-1}). In Georgia, Bullock and Goodroad (1989) obtained a significant yield responses at two locations on Norfolk and Tifton loamy sands in terms of corn grain to the application of 11 kg S ha^{-1} (10 lb S ac^{-1} ≡ 54 lb gypsum ac^{-1}). Mitchell et al. (1988) working in Alabama at 3 sites, found no wheat yield responses to applications of S up to 80 lb S ac^{-1} (430 lb gypsum ac^{-1}) although the S content of the tissue at growth stage 8 was significantly increased. However in other work at 2 different sites, (Golden, 1979; Mitchell and Mullins, 1990b; Mullins and Mitchell, 1990a), wheat yield responses were obtained to rates up to 80 lb S ac^{-1} (430 lb gypsum ac^{-1}).

Mullins and Mitchell (1990b) and Mullins and Mitchell (1991) obtained yield responses to applications of phosphogypsum at rates of up to 45 kg S ha^{-1} (40 lb S ac^{-1} ≡ 215 lb gypsum ac^{-1}) at 2 sites in Alabama (Table 4.13). When applied at this rate, there were no differences in yield between mined and phosphogypsum.

Based on these results, Mitchell and Mullins (1990a) and Mitchell et al. (1991) came to the conclusion that 22 kg S ha^{-1} (20 lb S ac^{-1} = 108 lb gypsum ac^{-1}) should be recommended for wheat at growth stage 4 on sandy Coastal Plain soils but that 44 kg S ha^{-1} (40 lb S ac^{-1} ≡ 215 lb gypsum ac^{-1}) may be needed if S is applied in split applications.

Eichorn et al. (1990) reported that an annual application of 108 kg S ha^{-1} (96 lb S ac^{-1} ≡ 516 lb gypsum ac^{-1}) as gypsum increased the yield of bermudagrass hay by 16% over a 4-year period and also its digestability. Rechcigl and Payne (1988) found that applications of 2240 to 4480 kg phosphogypsum ha^{-1} (2000 to 4000 lb ac^{-1}) depressed soil pH and reduced the yield of ryegrass below that of the control treatment. However on bahiagrass in a 3 year study on a Myakka sand, Rechcigl (l989) and Rechcigl et al. (1992) found applications of between 200 and 400 kg phosphogypsum ha^{-1} (180 and 360 lb ac^{-1}) increased the dry matter yield of bahiagrass by as much as 28%.

In Arkansas, Mascagni et al. (1991) obtained yield responses in cotton to the application of 20 lb S ac^{-1} (108 lb gypsum ac^{-1}) on sandy soils in one out of three years. In Mississippi on a Marietta fine sandy loam with a relatively high soil test S level, Jones and Watson (1991) obtained yield responses in bermudagrass up to 16 kg S ha-' (14 lb S ac^{-1} ≡ 75 lb gypsum ac^{-1}) indicating that soil tests for S are often unreliable.

4.3. State Sulfur Recommendations

All the experimental data show that to obtain crop responses to S, rates between 10 and 30 lb S ac^{-1} (54 and 175 lb gypsum ac^{-1}) are usually sufficient particularly when additions to the soil are also being made in atmospheric fallout. This is reflected in the Cooperative Extension Service recommended rates for sulfur application to various crops which are presented in Table 4.14. Cooperative Extension Service recommended rates for sulfur application to various crops which are presented in Table 4.14.

Table 4.13 Effect of rates of phosphogypsum and N fertilizer of wheat forage yields in Alabama (Mullins and Mitchell, 1990b; Mullins and Mitchell, 1991)

N Rate	S Rate	Wheat forage yield (kg dry matter ha^{-1})					
kg ha^{-1}		Benndale fine sandy loam			Dothan fine sandy loam		
		1986-87	1987-88	1988-89	1986-87	1987-88	1988-89
134 (120)†	0	2288 (2037)	4922 (4382)	4108 (3657)	2671 (2378)	2770 (2466)	4276 (3806)
134 (120)	11 (10)	3074 (2737)	4997 (4449)	4421 (3936)	3169 (2821)	2781 (2476)	4331 (3856)
134 (120)	22 (20)	3067 (2731)	4989 (4442)	4271 (3802)	2928 (2606)	2991 (2663)	4766 (4243)
134 (120)	45 (40)	3239 (2884)	5150 (4585)	4296 (3824)	3315 (2951)	3179 (2830)	4595 (4090)
134 (120)	90 (80)	3214 (2861)	5119 (4557)	4518 (4022)	3177 (2828)	2990 (2662)	4457 (3968)
202 (180)	0	2908 (2589)	5224 (4651)	4756 (4234)	4146 (3692)	3039 (2706)	4872 (4337)
202 (180)	11 (10)	3057 (2722)	5515 (4910)	5126 (4564)	3963 (3528)	3653 (3252)	4764 (4241)
202 (180)	22 (20)	2907 (2588)	5584 (4971)	5048 (4494)	3420 (3045)	3468 (3088)	4733 (4214)
202 (180)	45 (40)	3379 (3008)	5757 (5125)	5048 (4494)	4112 (3661)	3437 (3060)	5386 (4795)
202 (180)	90 (80)	3305 (2942)	5628 (5010)	4716 (4199)	4219 (3756)	3705 (3299)	4607 (4102)
$LSD_{0.05}$		246(219)	298(265)	181(161)	283 (252)	215(191)	285 (253)

† Values in () are in lb ac^{-1}

Table 4.14 Recommended rates of application for sulfur to crops in Southeastern states

State	Crop	S rate (lb ac^{-1})	Source
Alabama	All	10 (54)†	Adams et al. (1994)
Florida	Agronomic, grass	15-20 (80-108)	Hanlon et al. (1990); Kidder et al. (1990)
	Vegetables, citrus	No recommendation	Hochmuth and Hanlon (1989); Koo (1984)
Georgia	All	10 (54)	Plank (1989)
North Carolina	Corn, small grains, cotton, tomato, bermudagrass	20-30 (108-161)	Tucker and Rhodes (1987)
South Carolina	All	10 (54)	(Anon, 1982)
Tennessee	All	0	(Savoy et al., 1991)
Virginia	All	0	(Donohue and Hawkins, 1979)

† Gypsum equivalent

In California, Oster (1995) indicates that, while some responses to S are obtained in Northern California, he doubts whether gypsum would ever be used for this purpose as farmers prefer to use other chemical means. This opinion conflicts with the statement in Docket A-79-11,

> *that application rate for production (± 1-2 t ac^{-1}) is approximately equal to the rates reported in the TFI questionnaire.*

Thus, the maximum annual recommended application rate for phosphogypsum would be 161 lb ac^{-1} yr^{-1} for this use which is far below the EPA's assumed value of 1350 lb ac^{-1} yr^{-1}.

5. GYPSUM FOR SUBSOIL ACIDITY AMELIORATION

Sumner (1970) and Reeve and Sumner (1972) were the first to demonstrate that gypsum could be used for the amelioration of subsoil acidity. Subsequently, Hammel et al. (1985), Radcliffe et al. (1986) Sumner et al. (1986b), and Sumner (1990) obtained spectacular yield responses to the application of 5 and 10 t phosphogypsum and mined gypsum ha^{-1} (2.23 and 4.45 short t ac^{-1}) on a number of crops in Georgia on soils with acid Al-toxic subsoils. They found no difference in the yield of alfalfa when either mined or phosphogypsum was used (Table 5.1). A summary of the yield responses and economic analysis of the results for all the crops investigated at all sites is presented in Table 5.2.

Table 5.1 Effect of mined and phosphogypsum on the yield of alfalfa hay on a highly weathered acid soil (Sumner, 1990)

Treatment	Gypsum rate (t ha^{-1})	Alfalfa hay yield (kg ha^{-1})			
		1987	1988	1989	Total
Control	0	2375 (2114)[†]	5769 (5136)	7704 (6859)	15848 (14109)
Mined gypsum	5 (2.23)	3237 (2882)	6424 (5719)	8472 (7543)	18133 (16143)
	10 (4.45)	3828 (3408)	7323 (6520)	9726 (8650)	20877 (18586)
Phosphogypsum	5 (2.23)	3783 (3368)	7068 (6293)	8816 (7849)	19667 (17510)
	10 (4.45)	4041 (3598)	7647 (6808)	9453 (8416)	21141 (18822)
$LSD_{0.05}$		618 (550)	775 (690)	869 (774)	

[†] Values in () are in lb ac^{-1}

On very sandy soils such as the Ocilla in Table 5.2, poor responses to gypsum have been obtained often due to the excess Ca causing Mg and K to be leached out of the rootzone resulting in nutrient deficiencies (Syed-Omar and Sumner, 1991). Similar results to those in Table 5.2 were obtained by Rechcigl et al. (1988) in Virginia where the surface application of 13 t gypsum ha^{-1} (5.44 t ac^{-1}) resulted in a yield increase over 2 years while in Alabama, Odom (1991) increased the yield of irrigated alfalfa from 7200 to 9900 kg ha^{-1} (6410 to 8814 lb ac^{-1}) after the surface application of 10 t gypsum ha^{-1} (4.45 t ac^{-1}).

Caldwell et al. (1990), working in Louisana, reported that gypsum applied at 8.8 t ha^{-1} (4 t ac^{-1}) on an acid Gigger silt loam in 1986 increased cotton yields in the following 3 years. On the other hand, Mathews and Joost (1989) and Mathews and Joost (1990), also in Louisana, found phosphogypsum to be relatively ineffective in counteracting subsoil acidity in an Oliver silt loam. On an Ona fine sandy soil in Florida, Rechcigl et al. (1993) found that phosphogypsum at rates of 2.2 and 4.4 t ha^{-1} (1 and 2 t ac^{-1})

Table 5.2 Yield increases and net profit from various crops as a result of gypsum application to acid soils (Sumner, 1990)

Soil	Duration (y)	Crop	Gypsum rate (t ha^{-1})	Cumulative yield increase due to gypsum (kg ha^{-1})	Cost of gypsum ($)	Value of yield increase ($ ha^{-1})	Net profit due to gypsum ($ ha^{-1})
Appling	7	Alfalfa	10 (4.45)†	25000 (22257)	300	3750 [1518]¶	3450 [1397]
Dyke	4	Alfalfa	5 (2.23)	5500 (4897)	150	825 [334]	675 [273]
			10 (4.45)	5800 (5164)	300	870 [352]	570 [231]
Ocilla	3	Alfalfa	5 (2.23)	1500 (1335)	150	225 [91]	75 [30]
			10 (4.45)	4000 (3561)	300	600 [243]	300 [121]
Cecil	3	Alfalfa	10 (4.45)	5000 (4897)	300	750 [304]	450 [182]
Cecil	4	Cotton	10 (4.45)	900 (801)	300	1235 [500]	935 [378]
Appling	3a	Peaches	10 (4.45)	7500 (6677)	300	3947 [1598]	3647 [1477]
Appling	5	Soybeans	10 (4.45)	1730 (1540)	300	358 [145]	58 [23]

† Values in () are in lb ac^{-1}
¶ Values in [ ] are in $ ac^{-1}

reduced both root growth and dry matter yields of bahiagrass. Despite these sets of negative results, the literature contains much corroborative evidence for the beneficial effects of surface applied gypsum in promoting yields of various crops on a wide range of acid highly weathered soils (Shainberg et al., 1989; Alcordo and Rechcigl, 1993; Sumner, 1993a; Sumner, 1994).

The longevity of the surface applied treatment on the Appling soil in Table 5.2 has been followed for a continuous period of 13 years. Yield responses were obtained in each of the first 7 years of the experiment after which the experiment was discontinued but the plots were maintained to continue monitoring soil properties with time. The results presented in Figure 5.1 show that exchangeable Al has continued to decrease over the entire 13 year period indicating that yield responses were likely to have been obtained during this period. This is corroborated by the fact that a good stand of alfalfa has continued to grow on the gypsum treatments whereas on the control treatments, the alfalfa stand has been completely lost. These observations suggest that a onetime application of 10 t gypsum ha^{-1} (4.45 t ac^{-1}) is likely to last at least 10 years making the application rate the equivalent of 1000 kg gypsum ha^{-1} yr^{-1} (890 lb ac^{-1}).

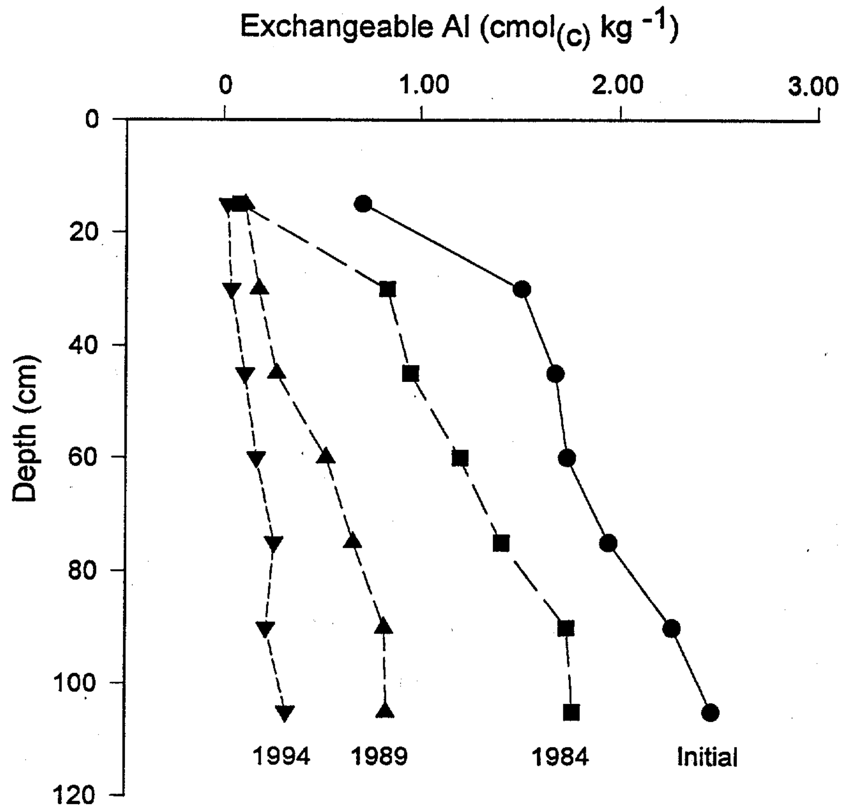

Figure 5.1 **Reduction in exchangeable aluminum over a period of 13 years subsequent to a single application of 10 t gypsum ha^{-1} (4.45 t ac^{-1}) on an Appling soil in Georgia**

5.1 State Gypsum Recommendations for Subsoil Acidity

Currently Georgia is the only state in the Southeast where gypsum is officially recommended for as an ameliorant for subsoil acidity (Sumner et al., 1989). The soils where responses are likely to occur are to be found mainly in the Piedmont and Appalachian Mountain regions of the Southeast. The recommended rate is 2-4 t ac^{-1} incorporated into the top 4-6 in once in five years. This would give a maximum annual application rate of 1600 lb phosphogypsum ac^{-1} (1797 kg ha^{-1}) for this recommendation. However in the light of the recent observation that the effect of gypsum on subsoil acidity is still obvious in terms of plant growth 13 years after application, this recommendation should be revised to 2-4 t gypsum ac^{-1} once in 10 years. On this basis, the maximum gypsum application rate would be 800 lb ac^{-1} yr^{-1}.

6. GYPSUM AS AN AMELIORANT FOR SOIL PHYSICAL PROPERTIES

Although gypsum has been widely used as an ameliorant for soils containing high levels of exchangeable Na (sodic soils) (Sumner, 1993b), it is only fairly recently that it has found use for improving infiltration and hydraulic conductivity of non-sodic dispersive soils (Shainberg et al., 1989). While the emphasis of this paper is on the latter category of soils, the discussion would not be complete without a brief mention of the former.

6.1 Reclamation of Sodic Soils

Gypsum is the most commonly used amendment for sodic soil reclamation, primarily because of its low cost. The poor physical condition of sodic soils is exacerbated when the electrolyte concentration in the soil solution is low. This occurs when rain or very high quality water (low elctrolyte concentration) are applied to soils resulting in marked decreases in hydraulic conductivity. Gypsum applied to a sodic soil increases permeability in two ways, namely, by increasing the electrolyte concentration in the soil solution and by reducing the proportion of Na occupying the CEC of the soil (Shainberg et al., 1989). In the past, the approach to reclaiming sodic soils was to apply Ca as gypsum equivalent to the quantity of exchangeable Na present in the soil and then leach the soil with water to effect its removal (US Salinity Lab Staff, 1954). This resulted in the recommendation of large amounts of gypsum often in excess of 60 t ha^{-1} (26 t ac^{-1}) during the reclamation period which often required a decade or more. Once reclamation had been achieved, the need for further gypsum applications would cease in most instances. Successful reclamation of sodic soils has been achieved with rates of gypsum varying from 10-100 t ha^{-1} (4.4-44 t ac^{-1}) but the preponderance of successes have been achieved at rates less than 60 t ha^{-1} (26 t ac^{-1}) (Rasmussen et al., 1972; Sharma et al., 1974; Prather et al., 1978; Abrol and Bhumbla, 1979; Merrill et al., 1980; Mishra, 1980; Oster, 1980). For example, Sharma et al. (1974) successfully reclaimed a sodic soil reducing exchangeable Na in the profile from 6.09 to 1.64 $cmol_c$

kg^{-1} after the application of 62 t gypsum ha^{-1} (27 t ac^{-1}) with deep tillage. Rasmussen et al. (1972) achieved a similar level of success with 18 and 36 t gypsum ha^{-1} (8 and 16 t ac^{-1}) on a soil with an initial average profile ESP of 34. Only in exceptional cases have high rates such as 100 t ha^{-1} (44 t ac^{-1}) been needed (Prather et al., 1978). The gypsum requirement (GR) for reclamation in t ha^{-1} can be calculated from the following equation (Oster and Jayawardane, 1996):

$$GR = 0.0086\,(F)(D_s)(\rho_b)(CEC)(ESP_i - ESP_f)$$

where F = Ca-Na exchange efficiency factor (1.1-1.3) depending on ESP_f
D_s = soil depth (m) to be reclaimed
ρ_b = soil bulk density (t m^{-3}) (1.3-1.6)
CEC = cation exchange capacity (mmol$_c$ kg^{-1})
ESP_i = initial exchangeable Na percentage
ESP_f = final exchangeable Na percentage.

Assuming two depths of reclamation (0.5 and 1 m ≈ 20 and 40 in), F = 1.2, ρ_b = 1.5 and ESP_f = 10, the gypsum requirements obtained are presented in Table 6.1. A soil with an ESP of 30 represents a highly sodic soil which would be at the upper end of the range where reclamation might be considered. Soils with higher ESP levels would seldom be considered for reclamation.

Table 6.1 Calculated values of the gypsum requirement in t ha^{-1} for various soil conditions

ESP_i	CEC (mmol$_c$ kg^{-1})		
	100	300	500
Soil reclaimed to 50 cm (20 in)			
15	3.9 (1.7)†	11.7 (5.2)	19.4 (8.6)
20	7.7 (3.4)	23.1 (10.3)	38.7 (17.2)
30	15.5 (6.9)	46.5 (20.7)	77.4 (34.4)
40	23.2 (10.3)	69.6 (31.0)	116.1 (51.7)
Soil reclaimed to 1 m (40 in)			
15	7.7 (3.4)	23.1 (10.3)	38.7 (17.2)
20	15.5 (6.9)	46.5 (20.7)	77.4 (34.4)
30	31.0 (13.8)	93.0 (41.4)	154.8 (68.9)
40	46.4 (20.6)	139.2 (61.9)	232.2 (103.3)

† Values in () are in short t ac^{-1}

For a fine textured highly sodic soil (ESP_1 = 30; CEC = 500) which represents the upper end of soils likely to be reclaimed, a maximum of only 77.4 t gypsum ha^{-1} (34.4 t ac^{-1}) would be required for satisfactory reclamation to a depth of 50 cm (20 in) according to the proposals of Oster (1994). In fact, there is evidence that this formula may overestimate the amount of gypsum required for reclamation. The data of Rasmussen et al. (1972) would tend to bear this out (Table 6.2).

Table 6.2 Effect of gypsum rates on the reclamation of a highly sodic soil (Rasmussen et al., 1972)

Treatment	ESP at different depths (cm) 5 years after gypsum application					Total alfalfa yield in last 3 years
	0-20 (0-8)†	20-28 (8-11)	28-40 (11-16)	40-60 (16-24)	60-90 (24-36)	t ha^{-1}
Control	13	23	37	38	47	2.5 (1.11)
18 t Gypsum ha^{-1} (8 t ac^{-1}) plowed to 90 cm (35 in)	2	4	7	9	12	11.2 (4.99)
36 t Gypsum ha^{-1} (16 t ac^{-1}) plowed to 90 cm (35 in)	2	4	7	10	15	13.1 (5.83)

† Depth in inches and yield in t ac^{-1}

Calculating a weighted ESP for the profile, one obtains values of 34, 8, and 9 for the control, 18, and 36 t gypsum ha^{-1} treatments, respectively. Thus from Table 6.1, one, can expect that the gypsum requirement for this soil would have been between 31 and 62 t gypsum ha^{-1} (13.8 and 27.6 t ac^{-1}) as this was a medium textured soil and the CEC would have been between 100 and 200 $mmol_c$ kg^{-1}. However this soil was successfully reclaimed with much lower levels of gypsum probably due to the fact that considerable calcium carbonate ($CaCO_3$) was present in the profile aiding in the reclamation process (Shainberg et al., 1989). This is an important point as many sodic soils contain considerable quantities of $CaCO_3$, and therefore lower amounts of gypsum will be required for reclamation than predicted by the gypsum requirement equation. In fact, Oster et al. (1995) indicate that, when calcareous sodic soils are cropped during reclamation, the primary source of Ca was from calcite (lime) which, together with extra water, is effective in bringing about satisfactory reclamation. This would reduce the area of sodic soils requiring gypsum for reclamation. In addition, some sodic soils naturally contain gypsum and can be readily reclaimed by leaching and deep tillage without any further applications.

Because of large variations in the exchangeable Na content of soils and in the time required to effect reclamation, it is difficult to calculate with any accuracy an annual gypsum requirement. On the other hand, the EPA in its Final Rule on phosphogypsum used the value of 2700 lb ac^{-1} applied biennially which would result in a gypsum application of approximately 68 t ac^{-1} (152 t ha^{-1}) in a period of 100 years which is considerably larger than that required to reclaim even a fine textured, highly sodic soil (ESP = 30 to a depth of 20 in) using the above approach. As most sodic soils are irrigated, a reclaimed rooting depth of 20 in is sufficient for optimal yields of many crops, although for grapevines greater depths may be required. These calculations agree well with the results of field reclamation experiments described above and should be used as the basis for calculating the risk assessments associated with phosphogypsum use rather than the basis used in Docket A-79-11.

In most sodic soil reclamation attempts, little attention was paid to the electrolyte effect in preventing clay dispersion and promoting hydraulic conductivity and, possibly, too much attention was concentrated on removing exchangeable Na from the soil profile. The relative importance of these two effects determines the amount of gypsum required for reclamation (Shainberg et al., 1989). If the electrolyte effect is sufficiently great, gypsum can be surface applied. The amount required depends on the quantity of high quality water to be used and the rate of gypsum dissolution and is somewhat independent of the level of exchangeable Na in the profile. (In California, some water sources are not of high quality containing substantial levels of salts which have essentially the same effect as the gypsum in flocculating clay.) Because the electrolyte effect gives rise to very rapid improvements in soil hydraulic properties and requires relatively small but frequent applications of gypsum, reclamation with this objective will be more efficient requiring less gypsum to achieve an acceptable soil physical condition. Conversely in soils where the CEC effect is of greater importance, the gypsum requirement depends on the quantity of exchangeable Na in the profile to a given depth. Oster and Frenkel (1980) have demonstrated that the reduction in ESP on irrigation and leaching is primarily limited to the soil depth to which the gypsum has been incorporated. This is a consequence of the greater selectivity of exchange sites for Ca than Na. In addition, recent advances in the reclamation of sodic soils involving a combination of gypsum applications with tillage operations and improved cropping systems have resulted in the more efficient usage of gypsum (Oster et al., 1995; 1996). Thus, large applications to reclaim sodic soils are likely to decrease in the future if the new approaches are implemented. Oster (1995) has indicated that, in commercial agriculture in California, an application rate of 50 t gypsum ac^{-1} spread over a 5-8 year period would be the maximum ever used. Sometimes gypsum at the equivalent of 1 t ac^{-1} is added to irrigation water to bring about reclamation in tree and vine crops but Oster (1995) stated that, because of the physical properties of phosphogypsum, it would seldom be used for this purpose.

When best management approaches are implemented in the reclamation of sodic soils, gypsum applications averaging between 200 and 800 lb ac^{-1} yr^{-1} are preferable rather than 1350 lb ac^{-1} yr^{-1} if applications continue for 100 years as assumed by the EPA. In fact, much greater weight should be placed on the lower end of this range in gypsum usage calculations because the least sodic soils are likely to receive attention first.

6.2 Crusting and Seedling Emergence

Many soils which are not sodic, readily form crusts at the surface which limit the rate of water entry into the soil resulting in increased runoff and erosion. This was first demonstrated in Georgia by Miller and Baharuddin (1986) who found strong correlations between various soil dispersability indices and infiltration rate and soil loss. Subsequently, Miller (1987, 1988) demonstrated that the cumulative and steady state infiltration rates of dispersive soils could be markedly increased by applying by-product gypsum such as phosphogypsum on the soil surface after completion of tillage operations and prior to the first rain. This effect could be maintained for four rainfall events (Table 6.3). His data clearly indicate that the effect is achieved by increasing the electrolyte concentration in the water at the soil surface which prevents clay dispersion and thus crust formation.

Similar results were obtained for a Coastal Plain soil on which phosphogypsum at 5 t ha^{-1} (2.23 t ac^{-1}) was effective in maintaining the mean infiltration rate at 13.8 cm h^{-1}. The control treatment (water only) was reduced to 7.4 cm h^{-1} (Miller and Scifres, 1988). Other confirmatory data have been published by Radcliffe et al. (1987) for soils on the Georgia Piedmont. In a field study with winter wheat on an Appling sandy loam soil, surface application of as little as 2 t gypsum ha^{-1} (0.9 t ac^{-1}) was very effective in reducing the cumulative soil loss over the growing season (Figure 6.1) (Miller, 1988). Adding gypsum at higher rates produced very little improvement indicating that the lowest rate was sufficient to reduce crusting, runoff, and erosion.

The effectiveness of gypsum in reducing clay dispersion and increasing infiltration was demonstrated by Miller et al. (1991) (Figure 6.2). In a rainfall simulation experiment in which water and gypsum solutions of different strength were compared, an electrical conductivity (EC) of 500 µmhos cm^{-1} was sufficient to prevent clay dispersion and maintain the infiltration rate. Using the same two soils, a separate experiment (Figure 6.3) demonstrated that most of the clay was flocculated at an EC greater than 500 µmhos cm^{-1}.

Gypsum applied on the soil surface to reduce runoff and erosion should be considered as an interim measure with bare soil. In the long term, vegetative cover is much more effective and therefore, gypsum would only be recommended during the establishment phase of the vegetative cover. This is clearly illustrated by the data of Radcliffe et al.

Table 6.3 **Effect of gypsum application at 5 t ha^{-1} (2.23 t ac^{-1}) on infiltration and soil loss from three Georgia soils (Miller, 1987; 1988)**

Variable[§]	Dry event			Wet event 1			Wet event 2			Wet event 3		
	CON		GYP	CON		GYP	CON		GYP	CON		GYP
						Cecil soil						
CI (mm)	30	*	43	5.5	*	13	4.6	*	12	4.1	*	12
IR (mm h^{-1})	30	*	43	11	*	25	9.5	*	25	8.5	*	23
Soil loss (kg ha^{-1})	266	*	96	149		141	155		134	157		130
Sed.Conc. (g L^{-1})	1.3		1.4	0.8	*	1.4	0.8		1.0	0.8	†	1.0
EC (mS m^{-1})	0.1	*	9.3	0.1	*	7.3	0.1	$\underline{*}$	5.6	0.1	*	4.3
						Worsham soil						
CI (mm)	12	*	20	1.7	†	3.1	1.4	$\underline{*}$	2.7	0.9		1.7
IR (mm h^{-1})	12	*	20	3.6	†	6.4	2.3	$\underline{\dagger}$	5.7	1.6		3.1
Soil loss (kg ha^{-1})	1315	†	732	691	†	328	871	$\underline{*}$	406	885	†	456
Sed.Conc. (g L^{-1})	4.0		3.0	3.1		1.6	3.9	$\underline{*}$	2.0	4.3	†	2.2
EC (mS m^{-1})	0.5	*	13	0.4	*	12	0.2	$\underline{*}$	12	0.2	*	13
						Wedowee soil						
CI (mm)	13	*	31	2.3	*	7.1	1.5	$\underline{*}$	5.5	1.8	*	5.2
IR (mm h^{-1})	13	*	31	4.7	*	15	3.2	$\underline{*}$	11	3.6	*	11
Soil loss (kg ha^{-1})	1135	†	442	521	†	266	589	$\underline{\dagger}$	305	601	†	309
Sed.Conc. (g L^{-1})	3.4		3.1	2.6		1.8	2.8	$\underline{\dagger}$	1.8	2.9		1.9
EC (mS m^{-1})	0.5	*	13	0.2	*	12	0.1	$\underline{*}$	11	0.2	*	11

[§] CI = Cumulative infiltration, IR = Infiltration rate, and EC = Electrical conductivity
† Significant at the 5% level
* Significant at the 1% level

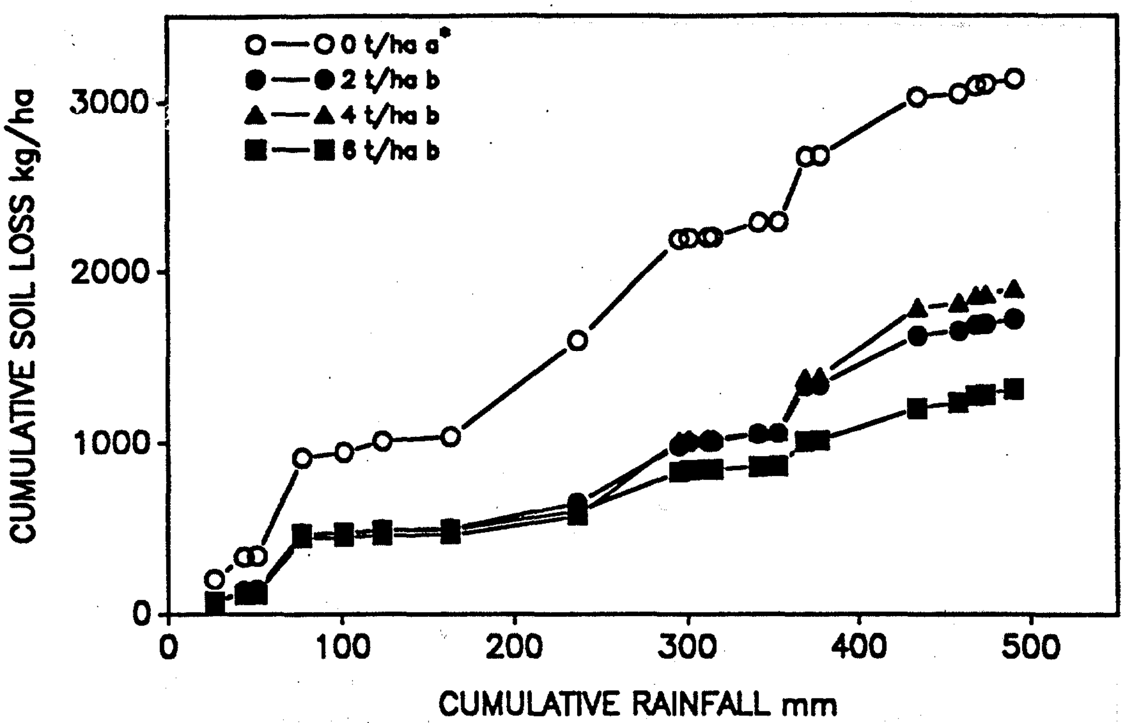

Figure 6.1 **Effect of surface-applied phosphogypsum on the cumulative soil loss during the winter growing season for wheat under natural rainfall (Miller, 1988)**

(1987) and Miller (1988) in which the relative effectiveness of phosphogypsum under conventional and no-till regimes for soybean production was compared (Figure 6.4). (No-till refers to the situation where each crop is directly drilled into the stubble of the previous crop without any tillage in which the soil surface is constantly protected from the impact of falling raindrops.)

While gypsum has an effect on both runoff and soil loss, its effect is greatest under conventional tillage where the soil surface is exposed to the maximum extent. In Australia, where highly dispersive soils are widespread, Hamblin and Howell (1988) also indicate that gypsum usage is not the long-term solution to crusting, largely because of economic considerations, but that gypsum has a useful role to play in an integrated crop management system where it is used to improve aggregation during establishment of no-till and/or pasture crops. Oster (1995) indicates that, for infiltration problems in California, a surface application of 1 t gypsum ac^{-1} yr^{-1} is the recommended rate but frequent annual usage would be unlikeiy.

When a soil crust forms and then dries out, strength sufficient to impair the emergence of crop seedlings often develops. Application of phosphogypsum over the row in a band at 0.2 kg m^{-1} (0.17 lb yd^{-1}), an application rate of approximately 200 kg ha^{-1} (178 lb ac^{-1}), can be effective in increasing the stand of the crop as was illustrated by Miller (1988) in Table 6.3.

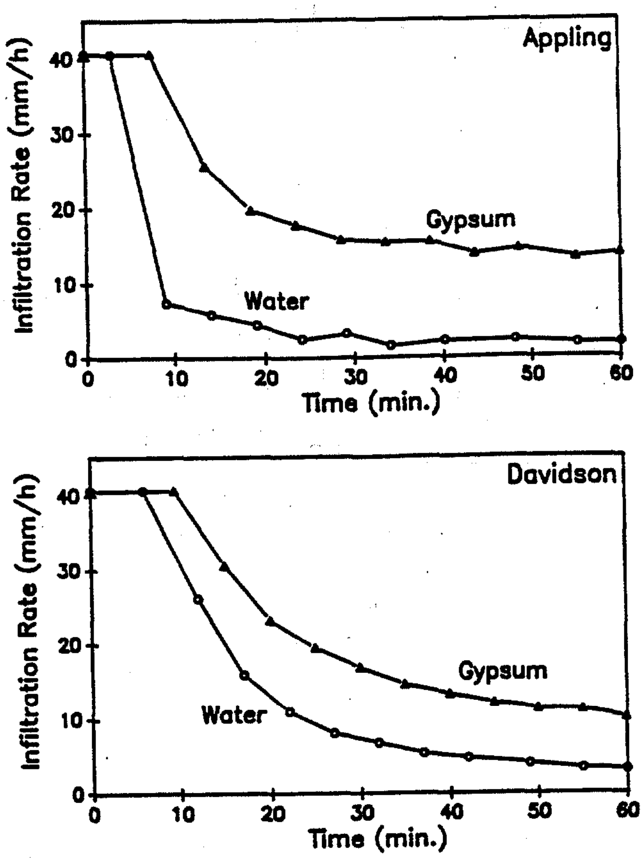

Figure 6.2 **Effect of deionized water and phosphogypsum solution (EC = 500 μmhos cm^{-1}) on the infiltration rates of two Ultisols from Georgia (Miller et al., 1991)**

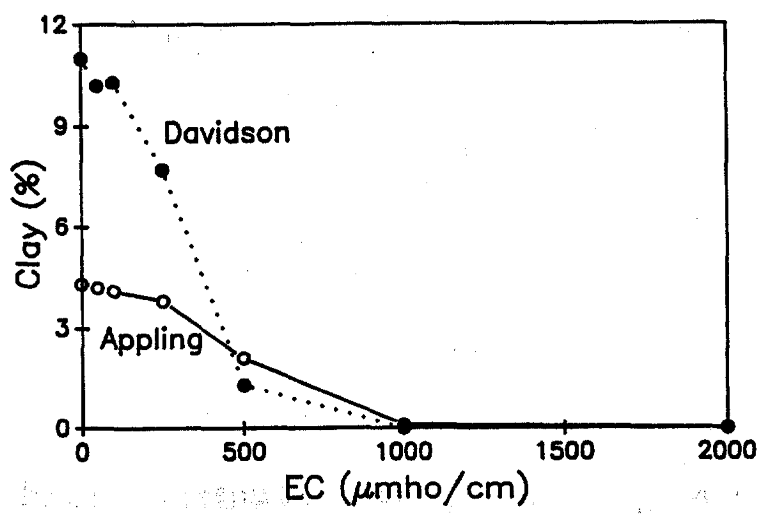

Figure 6.3 **Effect of electrical conductivity on clay dispersed by shaking two Georgia Ultisols overnight (Miller et al., 1991)**

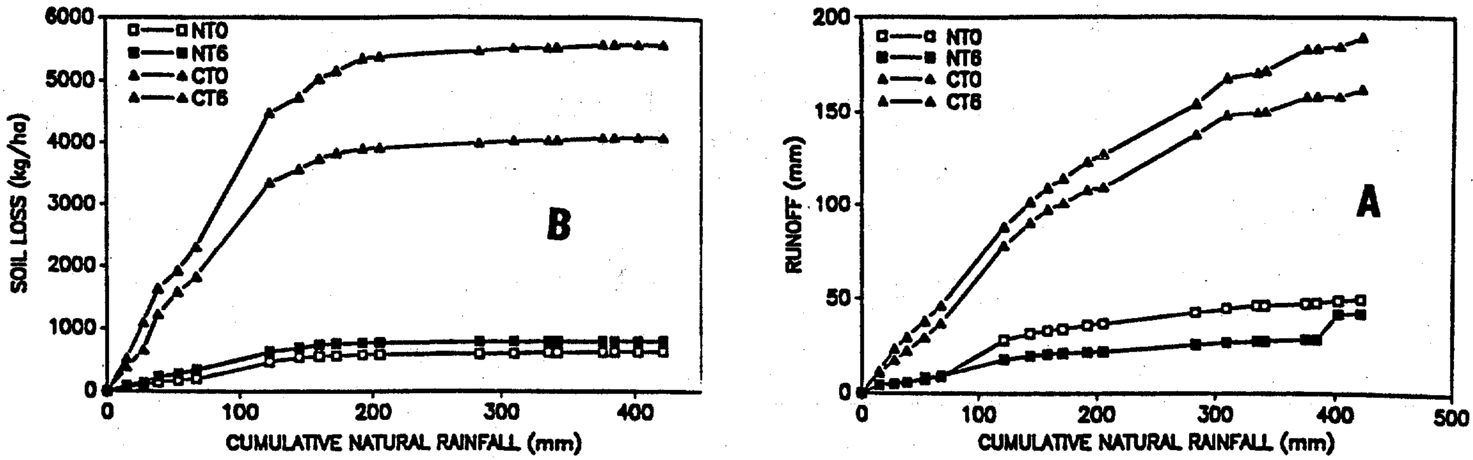

Figure 6.4 **Effect of surface-applied phosphogypsum and residue cover on runoff (A) and soil loss (B)during the growing season for soybeans under natural rainfall (NT = No-till, CT = Conventional tillage, 0 = No gypsum, 6 = 6 t gypsum ha^{-1} [2.7 t ac^{-1}]) (Radcliffe et al., 1987; Miller, 1988)**

Table 6.3 **Effect of phosphogypsum banded over the row on cotton seedling emergence on a Norfolk sandy loam soil (Miller, 1988)**

Treatment	Days after planting						
	3	4	5	7	9	10	12
	Seedling emergence (%)						
Control	12	22	35	46	56	65	68
Gypsum	37	45	55	67	69	74	79

As far as the longevity of the gypsum effect is concerned, Miller (1988) pointed out that small rather than large application rates would have the greatest benefit in maintaining surface soil structure. He recommended rates between 0.1 and 0.2 kg m^{-1} of row (0.09 to 0.17 lb yd^{-1} ≡ 178 lb ac^{-1}) until satisfactory vegetative cover could be established after which gypsum applications would no longer be necessary.

6.3 Hydraulic Conductivity

Although they used $CaCl_2$ in their laboratory experiments, Chiang et al. (1987) demonstrated that as little as 5 $mmol_c$ L^{-1} of salt in the soil solution had a large beneficial effect on the hydraulic conductivity of undisturbed Cecil and Davidson soil columns in Georgia. Although it is difficult to accurately determine what rate of gypsum applied to the soil surface would be likely to have the same effect, O'Brien and Sumner (1988) demonstrated that such a concentration could easily be subtended in the soil solution for a considerable period of time by a single surface application of 10 t gypsum ha^{-1} (4.45 t ac^{-1}). Unfortunately this work has not been followed up in the field.

In two-year studies with sugarcane in Louisana, Breithaupt (1983) and Buselli (1983) obtained significant yield increases in cane and sugar to applications of fluoro- and phosphogypsum as high as 22.4 t ha^{-1} (10 t ac^{-1}) on the Sharkey and Alligator clay soils. However, they were unable to successfully link the response obtained to any improvement in the physical properties of either soil. Research work in this arena is in its infancy and no recommendations for gypsum use to improve the hydraulic conductivity of non-sodic soils is currently being made.

6.4 Mechanical Impedence

Because it promotes clay flocculation, the possibility that gypsum may reduce the mechanical strength of subsoil pans that commonly occur in Southeastern soils was investigated by Radcliffe et al. (1986) on the Appling and Cecil soils described under Section 5 . They found that gypsum given sufficient time to dissolve and move down the profile significantly reduced the mechanical impedence of the subsoil, as measured by the cone index (Cl) value (Figure 6.5). The reduction in Cl appears to be brought about by improved soil structure in the subsoil, as measured by aggregate stability in water. Recent measurements on the treatments in these experiments 13 years after the treatments were made have shown that the effect is still manifest, albeit the differences due to gypsum being somewhat smaller than when measured earlier.

Due to the longevity of this effect, the application rate on an annual basis for this purpose would be 780 kg ha^{-1} (700 lb ac^{-1}). However no farmers have yet adopted this strategy due to the large initial cost.

6.5 State Gypsum Recommendations for Soil Physical Properties

For amelioration of crusting, the recommended rate in Georgia is 0.5-1 t gypsum ac^{-1} broadcast on newly prepared seedbeds after planting as an interim measure during the establishment of a permanent cover or no-till system (Sumner et al., 1989). In California, the recommended rate is 1 t gypsum ac^{-1} on an infrequent basis (Oster, 1995). For subsoil hardpans, the recommended rate is 1-2 t gypsum ac^{-1} once in five years (Sumner et al., 1989). This would give a maximum long-term annual application rate of 800 lb phosphogypsum ac^{-1} (900 kg ha^{-1}) for the improvement of soil physical properties.

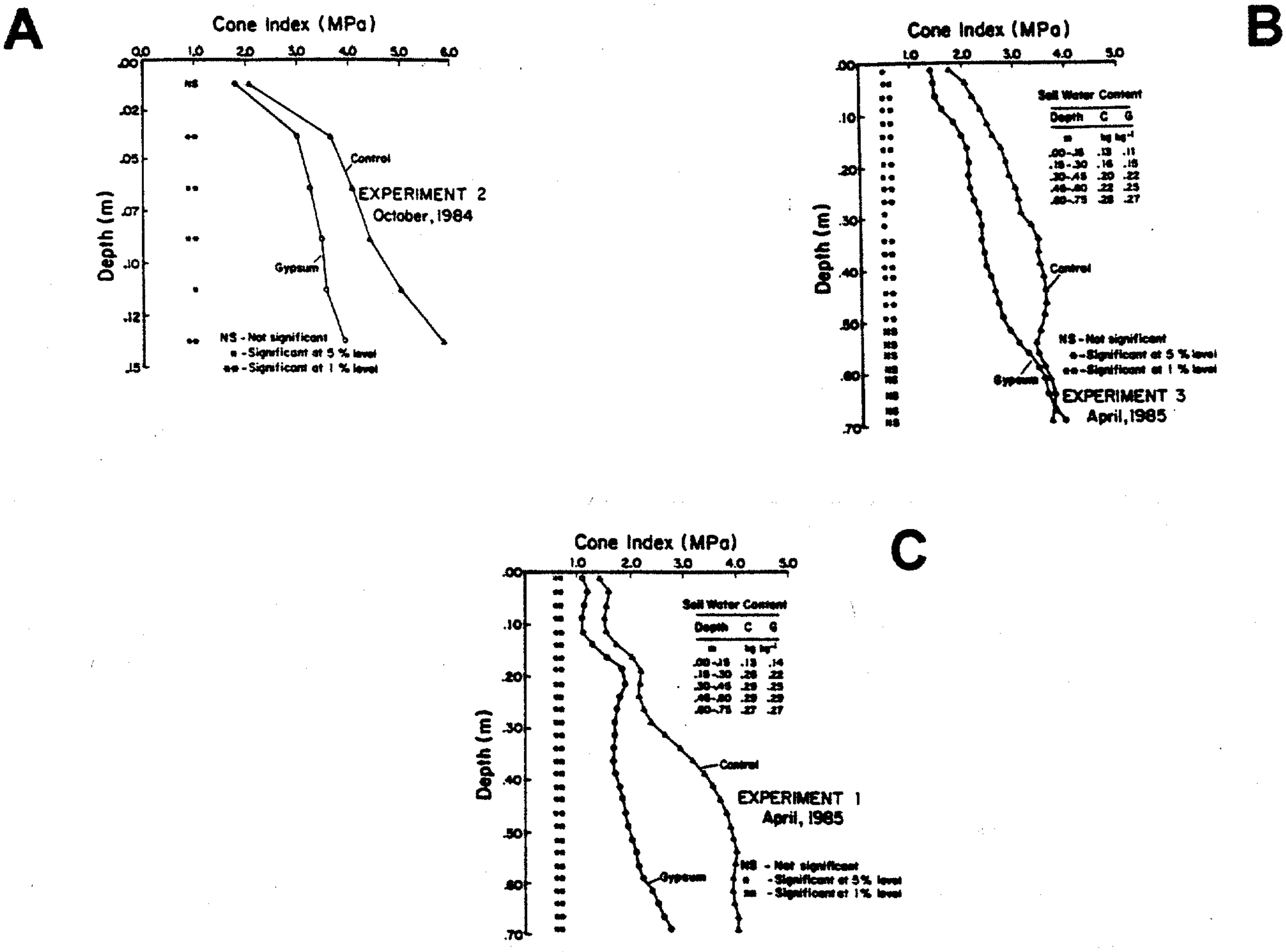

Figure 6.5 **Effect of gypsum as a single 10 t ha^{-1} (4.45 t ac^{-1}) application on mechanical impedance as measured by the cone index of soil profiles of the Appling coarse sandy loam in different experiments (A). 3 yr after application, (B). 3 yr after application and (C). 4 yr after application (Radcliffe et al. (1986)**

7. ENVIRONMENTAL IMPACTS ASSOCIATED WITH THE AGRICULTURAL USE OF PHOSPHOGYPSUM

7.1 Radiation

7.1.1 Application Rates

Phosphogypsum contains significant concentrations of a number of radionuclides, principally ^{226}Ra that decays to ^{222}Rn, and subsequently, to a number of other daughter products. Amacher and Miller (1986) assessed the environmental impacts of these contaminants when phosphogypsum is used as a soil additive. Assuming a ^{226}Ra

content of 25 pCi g^{-1} (0.925 Bq g^{-1}) in phosphogypsum and that negligible amounts of ^{226}Ra will be lost from the soil by leaching or plant uptake, they calculated the expected annual and cumulative concentrations of ^{226}Ra in soil for different application rates (Table 7.1).

Thus, applications of 4 t phosphogypsum ha^{-1} yr^{-1} (1.8 t ac^{-1} yr^{-1}) would have to be made to reach a level of 5 nCi ^{226}Ra kg^{-1} (185 Bq kg^{-1}) of soil which, at one time, was considered by the Federal Government to be a reasonable limit for land contaminated by uranium mill tailings on which residences have been or will be constructed (Lindeken, 1980). At the 5 nCi ^{226}Ra kg^{-1} (185 Bq kg^{-1}) of soil concentration, the direct radiation exposure rate is about 7 μrad hr^{-1} (approximately equal to the average background exposure rate of 6 μrad h^{-1}) and the annual whole body radiation dose (40 hr wk^{-1}, 52 wk yr^{-1}) is about 15 mrem or 3% of the maximum permissible annual limit of 500 mrem for the general public (Amacher and Miller, 1986). This is a conservative standard, below which only limited exposure can occur. Upon reaching this level in the soil, they recommended close monitoring of the situation.

The levels of ^{226}Ra that are likely to result from applying phosphogypsum to various crops have been computed in Table 7.2. Thus, in the worst case senario in Table 7.2, only 1.57 nCi ^{226}Ra kg^{-1} (58.0 Bq kg^{-1}) would be added to soil during a 100-year period when a phosphogypsum material with a high ^{226}Ra activity (35 pCi g^{-1}) was used at the maximum recommended rates for crops grown in the southeastern United States. This is well below the threshold level of 5 nCi kg-' (185 Bq kg-') considered to be safe. Much of the phosphogypsum likely to be used in practice will have a ^{226}Ra activity much less than this level.

7.1.2 Experimental Evidence

Golden (1983) found that application of phosphogypsum at 1 t ac^{-1} on fine-textured Mississippi River bottom soils in Louisiana increased radioactivity over background in the topsoil, but there were no significant differences between treated and control plots in the topsoil or in the cane juice. In other work with phosphogypsum in Louisiana and Alabama, Golden (1979), Mitchell and Mullins (1990b), and Mullins and Mitchell (1990a) found no significant differences in the levels of ^{226}Ra in tissue due to the applications of rates up to 80 lb S ac^{-1} as phosphogypsum.

Amacher and Miller (1986) calculated that vegetables grown on a soil containing 5 nCi ^{226}Ra kg^{-1} (185 Bq kg^{-1}) would reach about 0.05 nCi ^{226}Ra kg^{-1} (1.85 Bq kg^{-1}) in their tissues resulting in a dietary intake of about 4 pCi kg^{-1} (0.15 Bq kg^{-1}) assuming that 80 g of vegetables d^{-1} are consumed. Based on the current average dietary intake of ^{226}Ra which is 0.7-2.1 pCi d^{-1} (0.03-0.08 Bq d^{-1}) , their calculations showed that the 50-year integrated radiation dose to bone from a dietary intake of 4 pCi d^{-1} (0.15 Bq d^{-1}) would be about 1.4 rem compared to the maximum permissible dose of 2 rem yr^{-1}. If the

Table 7.1 **Amounts of ^{226}Ra added to soil and time required to reach 5 nCi kg^{-1} (185 Bq kg^{-1}) as a result of phosphogypsum (PG) applications (Amacher and Miller, 1986)**

PG Rate	^{226}Ra Rate†	Cumulative ^{226}Ra additions after years of PG application					Time•
		5	10	25	50	100	
t ha^{-1} y^{-1}	pCi $kg^{-1}ha^{-1}$ yr^{-1}	nCi kg^{-1} soil					Years
1	12.5 (0.46)¶	0.062 [2.3]§	0.125 [4.6]	0.312 [11.6]	0.625 [23.2]	1.25 [46.3]	400
5	62.5 (2.31)	0.312 [11.6]	0.625 [23.2]	1.56 [57.8]	3.12 [115.6]	6.25 [231.5]	80
10	125 (4.63)	0.625 [23.2]	1.25 [46.3]	3.12 [115.6]	6.25 [231.5]	12.5 [463.0]	40
25	312.5 (11.57)	1.56 [57.8]	3.12 [115.6]	7.81 [289.3]	15.6 [577.8]	31.2 [1155.6]	16
50	625 (23.15)	3.12 [115.6]	6.25 [231.5]	15.6 [577.8]	31.2 [1155.6]	62.5 [2314.8]	8
100	1250 (46.30)	6.25 [231.5]	12.5 [463.0]	31.2 [1155.6]	62.5 [2314.8]	125 [4629.6]	4

† Assuming that 1 ha to a depth of 15 cm weighs 2 $\times 10^{6}$ kg
¶ Values in () are in Bq $kg^{-1}yr^{-1}$
§ Values in [ ] are in Bq kg^{-1}
• Time required for ^{226}Ra in the soil to reach 5 nCi kg^{-1} (185 Bq kg^{-1})

Table 7.2 **Calculated soil levels of ^{226}Ra which would result from the application of phosphogypsum of varying ^{226}Ra contents to various crops for 100 years**

Phosphogypsum Use	Maximum annual rate	Years applied	Cumulative soil ^{226}Ra at the indicated radiation level†		
			10 [0.37]• pCi g^{-1}	25 [0.93] pCi g^{-1}	35 [1.30] pCi g^{-1}
	kg ha^{-1}		nCi kg^{-1}		
Ca for peanuts¤	675 (600)¶	100	0.34 {12.6}§	0.85 {31.3}	1.17 {43.6}
Ca for other crops¤	482 (430)	100	0.24 {8.9}	0.61 {22.5}	0.84 {31.2}
S for crops	162 (144)	100	0.08 {3.0}	0.20 {7.4}	0.28 {10.4}
Subsoil acidity amelioration	900 (800)	100	0.45 {16.9}	1.12 {41.7}	1.57 {58.0}
Amelioration of crusting	450 (400)	100	0.22 {8.3}	0.56 {20.9}	0.78 {29.0}
Reclamation of sodic soils	790 (700)	100	0.39 {14.8}	0.98 {36.5}	1.37 {50.8}
Amelioration of subsoil hardpans	900 (800)	100	0.45 {16.9}	1.12 {41.7}	1.57 {58.0}

¤ Assuming that peanuts are grown in a two-tear rotation; † Assuming that 1 ha to a depth of 15 cm weighs 2 x10^{6} kg; ¶ Values in () are in lb ac^{-1}; • Values in [ ] are in Bq g^{-1}; § Values in {} are in Bq kg^{-1}

guidline of the maximum threshold for ^{226}Ra of 5 nCi kg^{-1} (185 Bq kg^{-1}) soil is accepted as being reasonable, there appears to be little risk in using recommended rates of phosphogypsum containing more than 10 pCi ^{226}Ra g^{-1} (0.37 Bq g^{-1}).

In support of this conclusion, Mays and Mortvedt (1986), using excessive rates of phosphogypsum up to 112 t ha^{-1} (50 t ac^{-1}), found that radioactivity levels in the grain of three crops were not affected by phosphogypsum applications (Table 7.3). In the 0-15 cm soil layer, ^{226}Ra increased from 34.8 to 73.3 Bq kg^{-1} (0.9-2.0 nCi kg^{-1}) but, at greater depths, there were no differences. At the highest rate (112 t ha^{-1} ≡ 50 t ac^{-1}), the level of ^{226}Ra in wheat grain was doubled, but they considered this to be relatively unimportant as the differential ^{226}Ra levels in soil were not manifest in the pattern of ^{226}Ra uptake by the crop.

Table 7.3 **Effect of phosphogypsum (PG) applications on levels of radioactivity in corn, wheat, and soybean grain (Mays and Mortvedt, 1986)**

PG Rate ($t\ ha^{-1}$)	Radioactivity added to soil ($Bq\ ha^{-1}$)	Radioactivity in grain ($Bq\ ha^{-1}$)		
		Corn	Wheat	Soybeans
0	0	548 [14.8]	1578 [42.6]	2587 [69.8]
22 (10)†	20.3×10^6 [0.55×10^6]¶	399 [10.8]	1417 [38.3]	1117 [30.2]
112 (50)	103.6×10^6 [2.8×10^6]	330 [8.9]	3120 [84.2]	1106 [29.9]

† Values in () are in $t\ ac^{-1}$; ¶ Values in [ ] are in $nCi\ ha^{-1}$

Mullins and Mitchell (1990b, 1991) evaluated the effects of the radioactivity contained in phosphogypsum on the activity in soil and forage samples from their S rate experiments discussed in Section 4.2 (Table 7.4). No significant increases in ^{226}Ra were observed in

Table 7.4 **Effect of S rates as phosphogypsum on levels of radioactivity in soil and wheat tissue (Mullins and Mitchell, 1990b; Mullins and Mitchell, 1991)**

S rate	Soil depth (cm)				Wheat forage	
	0-25	25-51	51-73	76-102	^{226}Ra	^{210}Po¶
$kg\ ha^{-1}$	$pCi\ ^{226}Ra\ g^{-1}$				$pCi\ g^{-1}$	
Benndale fine sandy loam						
0	0.15 [5.6]*	0.10 [3.7]	0.10 [3.7]	0.23 [8.5]	0.13 [4.8]	0.25 [9.3]
22 (20)†	0.15 [5.6]	0.18 [6.7]	0.18 [6.7]	0.10 [3.7]	0.10 [3.7]	0.17 [6.3]
45 (40)	0.10 [3.7]	0.15 [5.6]	0.10 [3.7]	0.08 [3.0]	0.10 [3.7]	0.20 [7.4]
$LSD_{0.05}$	NS¤	0.05 [1.9]	0.04 [1.5]	0.08 [3.0]	NS	--
Dothan fine sandy loam						
0	0.25 [9.3]	0.25 [9.3]	0.23 [8.5]	0.35 [13.0]	0.10 [3.7]	--§
22 (20)	0.30 [11.1]	0.23 [8.5]	0.23 [8.5]	0.33 [12.2]	0.15 [5.5]	0.10 [3.7]
45 (40)	0.25 [9.3]	0.18 [6.7]	0.20 [7.4]	0.28 [10.3]	0.18 [6.7]	0.17 [6.3]
$LSD_{0.05}$	NS	NS	NS	NS	NS	--

¶ Because ^{210}Po could not be detected in several samples, no statistical anaylses were performed
§ Unable to detect
† Values in () are in $lb\ ac^{-1}$;
* Values in [ ] are in $Bq\ g^{-1}$
¤ NS = non significant

the wheat tissue grown on either soil. On the Benndale soil, there was some evidence of movement of radioactivity down the profile, but at exceedingly low levels. In a more comprehensive field study of the impacts from radionuclides (0.655 Bq g^{-1}) in phosphogypsum at 10 t ha^{-1} (4.45 t ac^{-1}) at various locations 5 years after application, Miller and Sumner (1992) found very little evidence that the levels of ^{214}Pb, ^{214}Bi and ^{226}Ra were increased in the soil profile (Table 7.5). Values in the control treatments were generally higher than on the treatments with phosphogypsum. In addition, the background levels of all three isotopes were much higher than the amounts added by a factor of at least five.

Similarly, no differences in plant uptake, and seed and leaf concentrations of these radionuclides could be detected due to the phosphogypsum treatment (Table 7.6). In a leaching column study with the same soils, Miller and Sumner (1992) found no accumulation of ^{214}Pb ^{214}Bi, or ^{226}Ra below the point of placement in the topsoil on either soil but on the coarser-textured Tifton soil, significantly high but nevertheless very low concentrations of ^{226}Ra were found in the leachates from phosphogypsum treated columns (Figure 7.1). After the initial pulse of ^{226}Ra in the leachate from the phosphogypsum treated column, the concentration decreased rapidly to a level approximately that of the control. The highest concentration in the leachate was 0.033 Bq ^{226}Ra L^{-1} (0.89 pCi L^{-1}) which is well below the maximum allowed for drinking water (0.111 Bq L^{-1}) (3.0 pCi L^{-1}) (Anon 1985). The total amount of ^{226}RA found in the leachate after the passage of 100 cm of water through the column (equivalent to about one year's rainfall and probably five fold the amount which would pas through the column as leachate in the field) was 0.25 Bq (6.75 Ci), or about 5% of the amount added in the phosphogypsum.

Mullins and Mitchell (1990a) found no differences in the concentrations of ^{226}RA and ^{210}Po in wheat forage between control and phosphogypsum treatments. Similarly, Myhre et al. (1990) found that phosphogypsum applied at 2.24 ha^{-1} (1 t ac^{-1}) to citrus had no significant effect on the ^{226}RA juice concentration. Rechcigl et al. (1992) in Florida applied phosphogypsum at rates of 0 to 4 t ha^{-1} (0 to 1.8 t ac^{-1}) to a bahiagrass pasture and found that water samples from treated plots at a depth of 90-120 cm contained 0.085, 0.078, and 0.028 Bq L^{-1} (2.30, 2.11, and 0.76 pCi L^{-1}) of ^{226}Ra, ^{210}Po, and ^{210}Pb, respectively. All these values were not significantly different from the control treatment values and the ^{226}Ra values were below the drinking water limit (Anon 1985). In terms of plant uptake, Rechcigl et al. (1992) found no significant differences in the concentrations of ^{226}Ra ^{210}Po, and ^{210}Pb in bahiagrass with increasing phosphogypsum rate. In the case of ryegrass, the ^{226}Ra concentration was marginally significantly higher than in the control. In fact, there have been no reported cases where phosphogypsum applications to crops in the field in the southeast at recommended rates have resulted in substantially elevated levels of ^{226}Ra in plant tissues.

Table 7.5 **Effect of phosphogypsum (PG) and mined gypsum (MG) applications (10 t ha^{-1} ≡ 4.45 t ac^{-1}) on soil levels of radionuclides in Cecil/Appling and Ocilla soils (Miller and Sumner, 1992)**

Depth (cm)	Cecil/Appling soil				Tifton soil	
	Control	PG		MG	Control	PG
		Expt 1	Expt2			
			^{214}Pb (Bq kg^{-1})			
0-15	74.4±2[¤] (2.00±0.05)[†]	58.8±2 (1.59±0.05)	58.5±7 (1.58±0.19)	55.5±2 (1.50±0.05)	18.1±0.7 (0.49±0.02)	21.5±5.2 (0.58±0.14)
15-30	62.9±1 (1.70±0.03)	49.6±2 (1.34±0.05)	46.6±4 (1.26±0.11)	53.3±4 (1.44±0.11)	18.1±1.4 (0.49±0.04)	18.9±3.0 (0.51±0.08)
75-90	67.0±15 (1.81±0.40)	45.5±2 (1.23±0.05)	34.0±3 (0.92±0.08)	32.9±4 (0.89±0.11)	20.3±3.7 (0.55±0.10)	20.7±0.1 (0.56±0.03)
			^{214}Bi (Bq kg^{-1})			
0-15	71.4±2 (1.93±0.05)	60.3±3 (1.63±0.08)	55.5±3 (1.50±0.08)	52.9±3 (1.43±0.08)	17.8±0.7 (0.48±0.02)	21.1±4.8 (0.57±0.13)
15-30	61.1±1 (1.65±0.03)	47.4±3 (1.28±0.08)	45.1±4 (1.22±0.11)	51.4±6 (1.39±0.16)	17.4±1.0 (0.47±0.03)	19.2±2.6 (0.52±0.07)
75-90	64.4±13 (1.74±0.35)	43.7±4 (1128±0.11)	32.6±3 (0.88±0.08)	31.8±5 (0.86±0.14)	19.6±3.0 (0.53±0.08)	19.6±0.1 (0.55±0.00)
			^{226}Ra (Bq kg^{-1})			
0-15	67.3±1 (1.82±0.03)	67.3±4 (1.82±0.11)	52.9±3 (1.43±0.08)	51.8±3 (1.40±0.08)	27.4±8 (0.74±0.22)	27.0±7 (0.73±0.19)
15-30	67.7±4 (1.83±0.11)	47.4±10 (1.28±0.27)	43.7±6 (1.18±0.16)	63.3±23 (1.71±0.62)	21.5±3 (0.58±0.08)	23.3±3 (0.63±0.08)
75-90	57.7±4 (1.55±0.11)	31.1±27 (0.84±0.73)	21.8±19 (0.59±0.51)	33.7±7 (0.91±0.19)	26.6±2 (0.72±0.05)	23.3±2 (0.63±0.05)

[¤] Standard error
[†] Values in () are in nCi kg^{-1}

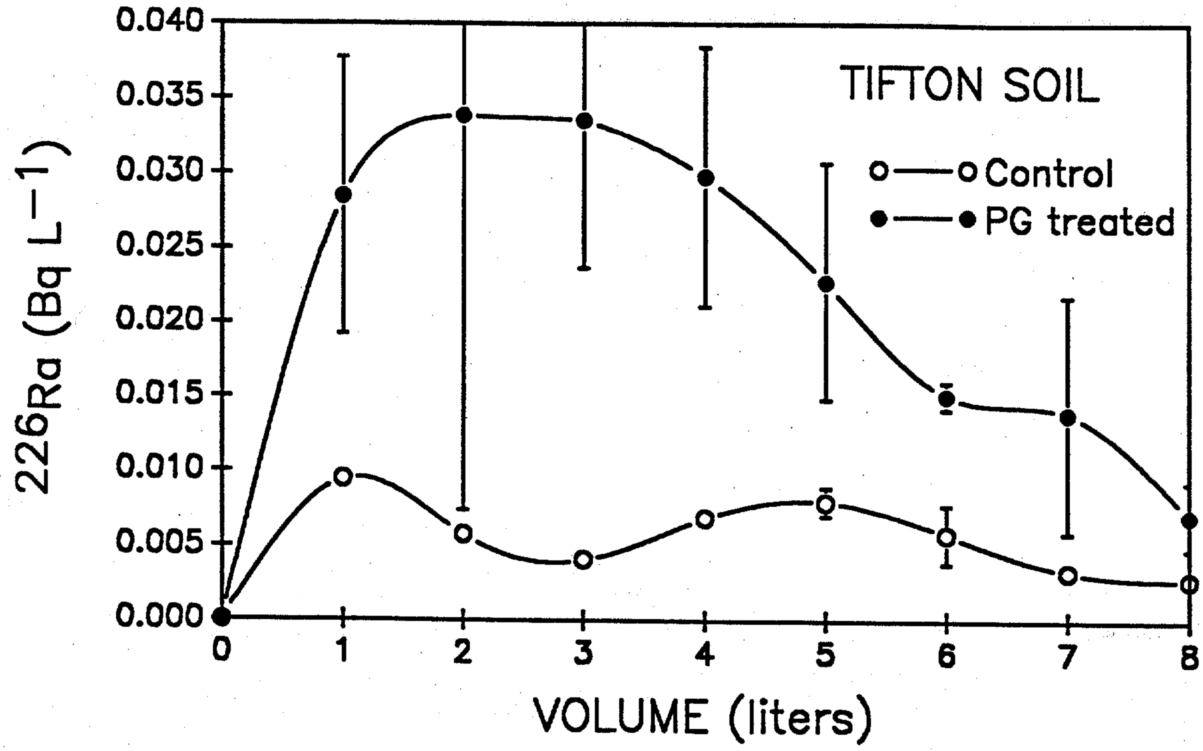

Figure 7.1 **Concentrations of ^{226}Ra in the leachate from columns of Tifton soil treated with phosphogypsum (Miller and Sumner, 1992)**

In 1980, Lindekin (1980) concluded that there is little concern associated with the uptake of ^{226}Ra by plants from soils treated with phosphogypsum. Based on the data accumulated since then and presented above, there appears to be no reason to modify this statement. Indeed, in most cases in the field, it has not been possible to show that addition of phosphogypsum containing more than the 10 pCi $^{226}Ra\ g^{-1}$ permitted in the Final Rule at recommended rates to soil for various purposes, has increased the levels of radiation in soil in the Southeastern United States above background nor is there any indication that ground-water supplies are likely to become contaminated with radiation in excess of the current drinking water standard.

8. DISCUSSION AND CONCLUSIONS

8.1 Potential Phosphogypsum Rates

This extensive review of the literature has been successful in identifying the maximum, minimum, and most likely application rates for phosphogypsum in agriculture in the Southeast, in particular. Because of the substantial body of scientific data on which these are based, they should be the foundation upon which all risk assessments

Table 7.6 **Effect of phosphogypsum (PG) and mined gypsum (MG) applied as a single application at a rate of 10 t ha^{-1} (4.45 t ac^{-1}) on radionuclide uptake by alfalfa at two locations in Georgia (Miller and Sumner, 1992)**

Isotope	Cecil/Appling soil				Tifton soil	
	Control	PG		MG	Control	PG
		Expt 1	Expt 2			
	Bq kg^{-1} dry tissue					
^{40}K	437±41[¤] (11.8±1.1)[†]	703±114 (19.0±3.1)	300±14 (8.1±0.4)	274±30 (7.4±0.8)	544±74 (14.7±2.0)	437±104 (11.8±2.8)
^{214}Pb	0.56±0.81 [15±22][¶]	0.89±0.77 [24±20]	0.86±0.74 [23±20]	1.89±1.26 [51±34]	3.07±0.19 [83±5]	2.74±1.07 [74±29]
^{214}Bi	1.15±0.30 [31±8]	1.67±0.63 [45±17]	1.44±0.37 [39±10]	2.01±1.33 [54±36]	3.26±0.19 [88±5]	2.92±1.70 [79±46]
^{226}Ra	32.9±4.2 [888±113]	20.8±16.6 [561±448]	30.1±7.2 [813±194]	28.0±4.0 [756±108]	73.5±4.4 [1984±119]	73.6±24.4 [1978±659]
^{210}Po	7.0±1.1 [189±30]	8.5±7.6 [230±205]	6.4±0.6 [173±16]	6.3±0.9 [170±24]	4.7±0.7 [127±19]	4.7±0.6 [127±16]

[†] Values in () are in nCi kg^{-1}
[¶] Values in [ ] are in pCi kg^{-1}
[¤] Standard error

associated with the use of phosphogypsum in agriculture are derived. These are superior to previous surveys of its use which have been made without due attention to the various practices that farmers are likely to use in the field. These rates are based upon the assumption that, on average over the years, the amount indicated in Table 8.1 will be applied to the same field.

Table 8.1 Maximum, minimum and most likely rates for gypsum use in agriculture

Gypsum Rate	Phosphogypsum use						
	Calcium supply to		Sulfur supply to all crops	Subsoil acidity	Physical properties		
	Peanut	Other crops			Sodic soils	Crusts	Hardpans
	$lb\ ac^{-1}\ yr^{-1}$						
Maximum	600	430	161	800	700	400	800
Most likely	125-430	200-300	50-80	400	200-500	100-200	400
Minimum	0-83	0-143	0	0	0-200	10	?

The highest gypsum use rate is for the amelioration of subsoil acidity and hardpans, the values for which were derived from the same experiment. The maximum value of 800 lb gypsum $ac^{-1}\ yr^{-1}$ is 1.7-fold less than the assumed EPA value of 1350 lb gypsum $ac^{-1}\ yr^{-1}$. The soils in the Southeast which are likely to respond to such applications of gypsum mostly occur in the Piedmont and Appalachian Mountain regions. In general, these soils are currently less intensively cultivated than the Coastal Plain. For this reason and because of the high cost of the large initial application of gypsum required to effect amelioration which can only be borne by high value crops, very little acreage is likely to be treated using this technology. Therefore the potential phosphogypsum tonnage likely to be sold in this area for this purpose is rather small.

The next highest gypsum use rate is for the amelioration of sodic soils, very few of which occur in the Southeast and therefore phosphogypsum use for this purpose will be infinitesmal. However in drier regions in the Western US where such soils occur relatively frequently, the maximum use rate of 700 lb gypsum $ac^{-1}\ yr^{-1}$ required to reclaim a highly sodic soil is almost half that assumed by the EPA. Furthermore, because the least sodic soils are likely to be reclaimed first, the rate used in practice is likely to be more of the order of 200-500 lb gypsum $ac^{-1}\ yr^{-1}$ which is between 2.7- and 6.8-fold less the the EPA value. This substantially alters the risk assessment calculations which are now likely to show that phosphogypsum use at recommended rates will be safe on agricultural soils.

In the Southeast, most of the potential for phosphogypsum usage is in the peanut industry where the sustained maximum rate for long-term application is 600 lb gypsum ac^{-1} yr^{-1} which is 2.3-fold less than the value used by the EPA in their risk assessment calculations. Because gypsum applications have been made to peanuts for many years and, because farmers have been diligent in neutralizing soil acidity with lime, the levels of Ca in the soils in this region are often above the threshold at which gypsum responses have been recorded. Moreover, the scientific data show that most of the gypsum responses in peanuts have been obtained with the large-seeded varieties which only occupy a portion of the acreage cultivated to this crop. Both these factors are likely to cause the gypsum application rate used most frequently to be less than the maximum and lie in the range 125-430 lb gypsum ac^{-1} yr^{-1} which is 3.1- to 10.8-fold lower than the EPA value.

Phosphogypsum use for other purposes such as the amelioration of soil crusting will occur at sustained rates much less than those discussed above, and therefore potential risk in these cases will be much less.

8.2 Radiation

Calculations show that, if a phosphogypsum material with a ^{226}Ra activity of 35 pCi g^{-1} (3.5-fold higher than that permitted in the Final Rule) was applied to soil in the same field at the maximum recommended rate for any use (800 lb ac^{-1} yr^{-1}) for 100 years, the total cumulative soil ^{226}Ra concentration is likely to be 1.57 nCi kg^{-1} (58.0 Bq kg^{-1}). This value is much less than the value of 5 nCi kg^{-1} (185.0 Bq kg^{-1}) which was proposed by the Federal Government as being a safe concentration in soils for housing development purposes.

Considerable experimental evidence from field trials in which phosphogypsum had been used at recommended rates has failed to show that radiation levels in soils or crops have been substantially increased. On the contrary, most of the evidence shows that the ^{226}Ra concentrations in soils and plants are seldom above the background levels present in untreated controls.

8.3 General Conclusion

In the light of the scientific literature reviewed in this document, the rate for phosphogypsum use in agriculture used in the development of the Final Rule on the National Emission Standards for Harzardous Air Pollutants (NESHAPS); National Emission Standard for Radon Emissions from Phosphogypsum Stacks is much higher than what the data would support. In addition, the levels of radiation measured in the field due to phosphogypsum additions to soils have been virtually indistinguishable from the background levels on control treatments where phosphogypsum was not applied. Therefore, the EPA should recalculate the current Final Rule on Phosphogypsum.

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