Publication No. 01-020-082

USE OF GYPSUM TO IMPROVE PHYSICAL PROPERTIES AND WATER RELATIONS IN SOUTHEASTERN SOILS

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Florida Institute of
Phosphate Research

Prepared By

University of Georgia
Research Foundation

Under a Grant Sponsored by the
Florida Institute of Phosphate Research
Bartow, Florida

DECEMBER 1989

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FINAL REPORT

PROJECT #83-01-020:

USE OF GYPSUM TO IMPROVE PHYSICAL PROPERTIES AND WATER RELATIONS IN SOUTHEASTERN SOILS

Submitted to

FLORIDA INSTITUTE OF PHOSPHATE RESEARCH

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September 5, 1998

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PERSPECTIVE

Dr. Steven G. Richardson, Reclamation Research Director

Phosphogypsum is a by-product of the wet-acid production of phosphoric acid. By the end of 1989, between 500 and 600 million tons will have accumulated in Florida, with about 30 million tons being added annually. A high priority research area at the Florida Institute of Phosphate Research has been to investigate potential uses for phosphogypsum in industry and agriculture. This project is one of several funded by the Institute to examine the use of phosphogypsum as an agricultural soil amendment.

In this report, Dr. William Miller of the University of Georgia has demonstrated how surface-applied gypsum could reduce soil crusting, improve infiltration of rainwater, and reduce soil erosion in several highly weathered soils in Georgia. The beneficial effects of gypsum were most striking in a heavier sandy clay loam, but lighter sandy loams also responded.

In other work at the University of Georgia (FIPR Project No. 83-01-024R) Dr. Malcolm Sumner has shown that by-product gypsum is effective in increasing yields of several field crops grown on acid soils by ameliorating aluminum toxicity and supplying additional calcium. Gypsum has an advantage over lime in that the slightly greater solubility of gypsum makes surface application possible, whereas lime often must be tilled deeply into the soil to be as effective.

Another project (FIPR No. 87-01-059) culminated in the publication of a comprehensive review article:

Shainberg, I., M.E. Sumner, W.P. Miller, M.P.W. Farina, M.A. Pavan, and M.V. Fey. 1989. Use of gypsum on soils: a review. Advances in Soil Science 9:1-111.

Dr. Arvel Hunter of Agro Services International has described how the application of by-product gypsum alone and in combination with other nutrients and additives affected yields and nutrient contents of various crops grown on sandy, low-cation-exchange soils in Florida (FIPR Project No. 84-01-034). Gypsum application resulted in increased yields of several crops, including corn, potatoes, cantaloupes and watermelons. An important point of this research was that the benefits of the calcium and sulfur in gypsum might not be fully realized unless other nutrient deficiencies in the soils are also corrected. The study also found no significant effects of 0.5 to 1.5 tons of phosphogypsum per acre on radioactivity (gross alpha and gross beta emissions) or concentrations of arsenic, copper, iron, manganese, cadmium, vanadium, or zinc in several vegetable and fruit crops.

Dr. Greg Mullins of Auburn University has examined the use of gypsum as a sulfur fertilizer for annual forages (FIPR Project No. 85-01-048). His research has shown increases in forage quality and yield due to the sulfur in gypsum, which depend not only on the amount but also on the timing of application. The need for sulfur fertilization was greater under a reduced tillage system than with conventional tillage. Soil and plant tissue samples have been analyzed for radium and polonium radionuclide concentrations. So far the analyses have shown no effects of phosphogypsum, applied at 40 to 80 pounds sulfur per acre, on radionuclide concentrations in either plants or soils.

TABLE OF CONTENTS

SUMMARY

The interaction of rainfall with the soil surface has a major effect on agricultural productivity and environmental quality in the Southeastern U. S. High-intensity rainfall during the summer months often causes surface crusting, which inhibits seedling emergence, decreases water infiltration into the soil, and causes accelerated soil erosion. Dispersion of soil clays and associated aggregate breakdown have been implicated in the process of soil crusting. The application of gypsum, particularly high-purity phosphogypsum, has the potential to flocculate soil clays into micro-aggregates, and thereby delay or decrease crust formation, provided that ionic strength of the soil solution is the primary factor responsible for de-flocculation.

The studies reported here show that gypsum does increase water intake rate and reduce soil loss, and that the mechanism is primarily an ionic strength effect. A new approach to simulating rainfall in the laboratory and field settings has been developed and tested, allowing runoff and erosion measurements to be more easily collected. The results from three soils tested under a single-nozzle simulator show significantly higher infiltration rates of soils receiving 5 mt/ha gypsum, with a 50% reduction in soil loss. The sediment produced from gypsum-amended plots was flocculated into silt-sized particles, which are less transportable and less likely to enter surface waters. In another experiment using a Greenville soil, Na- and $CaSO_4$ amendments also produced the expected results of respectively increasing runoff and erosion (for Na) and significantly decreasing both factors for Ca-treated soils.

Laboratory studies on selected topsoils have demonstrated the importance of soil pH, soil solution ionic strength, and sodium levels in determining dispersive behavior. Even low levels of sodium, coupled with the low ionic strength of

southeastern topsoils, leads to high dispersibility, which allows the fine fraction of the soil to clog water transmission pores and reduce water intake rates. Water conductivity decreases by a factor of two at sodium levels of 2-5% and ionic strength < 2 mM, compared to Ca-saturated systems at 5 mM, at pH 5-6. In a study of 9 Georgia topsoils, even a 10% saturation of gypsum in the solution phase caused significant flocculation of clays, although soils differed in their sensitivity to ionic strength changes. The flocculating effect of gypsum on phosphatic clays was evaluated in a separate study, and found to have little effect in the range of 10-20 % solids suspensions of the clays, largely because the clays were already flocculated in these concentrated suspensions.

Field studies on the Appling soil have shown the utility of surface-applied gypsum over the growing season in increasing water infiltration and decreasing soil loss. The longivity of this effect appears to extend over at least a crop growing season under average field conditions. Regular yearly applications, perhaps at a rate of 1-2 mt/ha, seem to be necessary for a continued effect, although longer-term changes in soil properties may also be occurring. In one study cotton emergence was marginally increased by gypsum application. The economics of gypsum use under this scenario are uncertain: yield increases demonstrated in other studies may marginally cover the costs of application for some crops on responsive soils, but not on others.

PROJECT RESULTS

I. Introduction

A major factor limiting crop yields in the Southeastern U.S. is an insufficiency in the total amount and availability of water. While part of this problem is attributable to high evaporation and plant transpiration rates, a considerable amount of rainfall fails to infiltrate into soils and is lost as runoff, subsequently causing high rates of soil erosion which have damaged many soils in this area. The critical factor in determining the partitioning of rainfall between infiltration and runoff is the stability of the structural units at the soil surface towards the beating action of raindrops, the impacts of which are capable of dispersing soil particles, clogging water transmission pores, and creating surface crusts (Tackett and Pearson, 1965; Quirk, 1978; 1979). Southeastern soils cropped to rowcrops with limited canopy development and root systems typically possess poor structural stability, and the result is often substantial loss of water and soil in runoff. Similarly, irrigated soils may accept added water only slowly because of puddled and crusted surface layers. Such crusting may delay or deter seedling emergence, and result in reduced stands after planting (Timm et al., 1971). These effects may be attributed to lack of organic binding agents in these soils (Harris et al., 1966; Tisdall and Oades, 1982; Lal, 1979), but other chemical factors, such as clay dispersibility, charge characteristics, pH, ionic strength, and inorganic binding agents may also play a significant role (Quirk and Schofield, 1955; McIntyre, 1958; Kamprath, 1971; Gillman, 1973; Shanmagamathan and Oades, 1982).

While soils high in sodium have been long recognized to benefit from applications of gypsum in improving their physical properties, recent studies in Israel and Australia have demonstrated the importance of dispersion in the crusting phenomena described above on non-sodic soils, and the amelioration of this syndrome by the use of surface applied gypsum. On dispersive, highly weathered soils in Australia, gypsum significantly increases water infiltration and reduces crusting associated with dispersion-induced sealing (Loveday, 1974; Rengasamy et al., 1984). Israeli soils similarly greatly improved in infiltration and hydraulic conductivity when treated with gypsum (Agassi et al., 1982; Kazman et al., 1983). Keren and Shainberg (1981) have shown that dissolution of surface-applied gypsum is responsible for flocculation of clays under raindrop impact, thereby maintaining a more porous surface layer and reducing runoff associated with pore collapse. By-product phosphogypsum was more effective than mined gypsum in this study due to its finer particle size and more rapid dissolution rate.

Given the similarities in soils between Georgia and other regions where gypsum has shown to be beneficial, the hypothesis of this project was that soils of the Southeast may undergo dispersion-induced crusting, and that by-product gypsum, readily available in Florida, may have a significant beneficial effect in reducing such crusting on cultivated soils. The overall objective of this project was therefore to demonstrate the agricultural value of by-product phosphogypsum with respect to its effect of soil physical properties and water relations. Two distinct phases of the research involved characterizing the soil response to applied gypsum in greenhouse and field tests with simulated rainfall, and then attempting to understand that response in terms of basic soil physical and chemical processes in the laboratory.

II. Runoff/Erosion Studies Using Phosphogypsum

This phase of the project attempted to quantify the effect of surface-applied phosphogypsum on water infiltration rate and soil loss. A major part of this effort was directed towards design and construction of a rain simulator that can be used to apply rainfall to indoor pan plots and field-scale plots, at intensities and with characteristics that approximate natural rain. The simulator was built during year 1 of the project, in both laboratory and field-scale versions. Laboratory studies were designed to evaluate a range of soil responses to applied gypsum, while necessarily more restricted field tests approximated conditions more likely under actual rainfall conditions.

A. Rainfall simulator design A major problem in collecting soil loss and infiltration data is the need to apply rainfall in repeatable, controlled amounts. An inexpensive, portable unit is highly desireable for this work as well. The unit developed during this project is shown schematically in Fig. 1. It consists of a wide angle square spray nozzle mounted in an electrically operated solenoid valve that can be remotely opened and closed to regulate the water flow to the plot below. The field unit shown uses three nozzles to apply rain to a 3 m by 1 m plot, which is enclosed by wooden plot boarders and equipped with a flume at the lower end. A plastic eccentric cam system is used to control solenoid opening and closed by operating switches riding on the cam. A microcomputer might be used to replace this system of solenoid control if equipment was available. A single-nozzle unit was built to be used in the greenhouse to apply rain to two 0.3 m^2 runoff pans, and operates in an analagous manner. This design is a novel approach to the problems inherent in simulating rainfall, and will expidite data collection and improve reproduction of natural rainfall characteristics.

Testing of the simulator units involves determining rainfall intensities

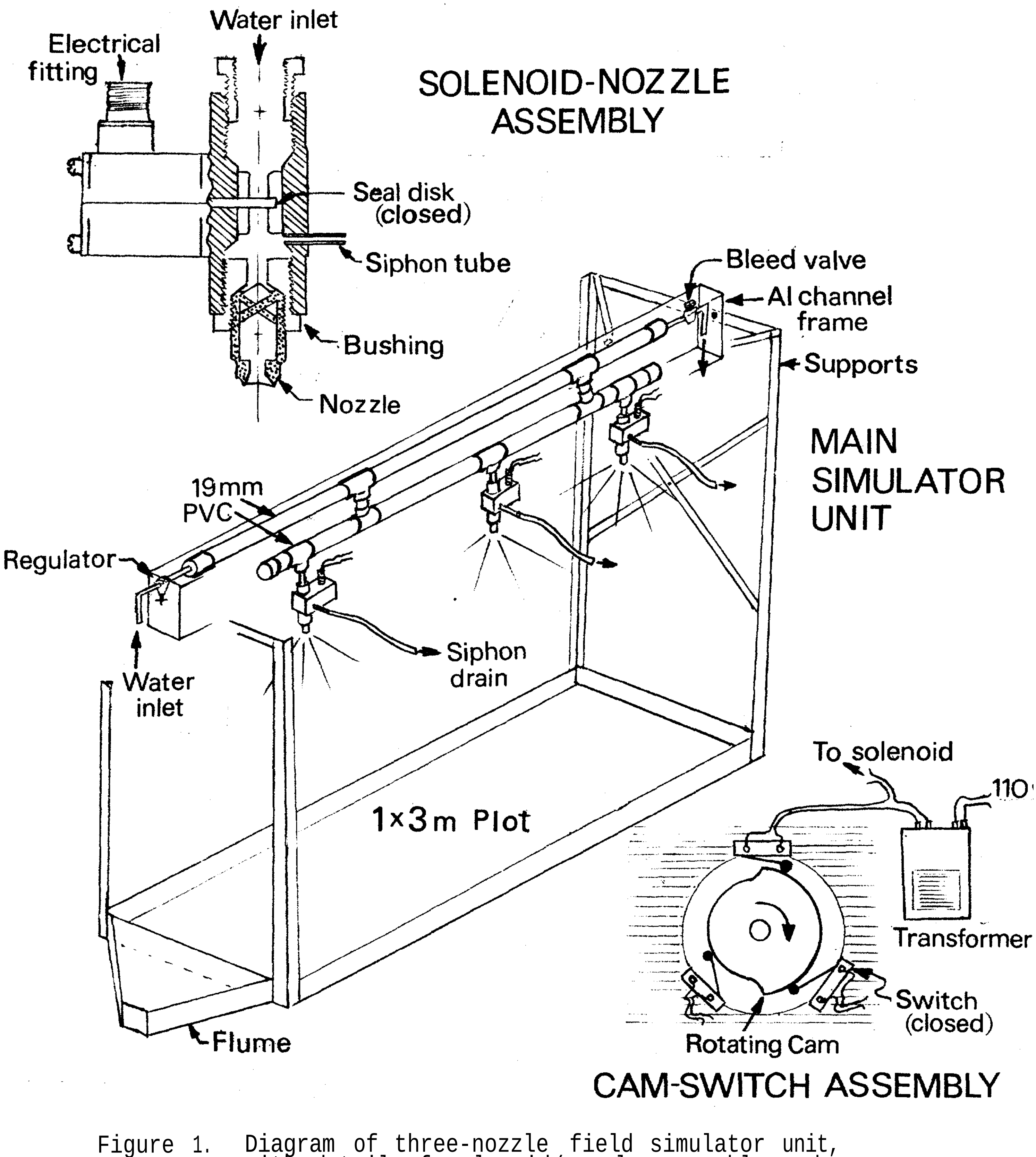

Figure 1. Diagram of three-nozzle field simulator unit, with detail of solenoid/nozzle assembly and motor-driven cam control assembly.

(which are varied by use of different sizes of lobed cams) and uniformities of rainfall. The simulators were run for a given time, during which 60-100 small containers placed on a grid below collected the rainfall. The volumes collected were converted to intensities, and standard statistics calculated. The results (Table 1) show that for the single nozzle greenhouse-based unit, varying the cam lobe angle resulted in intensities from 1.4 to 8.6 cm/hr, with uniformities (C.U.) of 90% or greater. These values are equal or superior to those of other simulators reported in the literature (Meyer, 1979). Uniformities are improved at a given intensity when the speed of cam rotation is reduced, allowing the solenoid to remain open for a longer time (i.e., up to 0.8 sec). However, long delay periods between solenoid openings are undesirable, and a speed of 20 rev/min seems the minimum

Table 1. Rainfall intensities and coefficients of uniformity and variation for l- and J-nozzle simulators at 29 kPa pressure.

Cam[1] lobe	Cam speed	Time open/closed	Rainfall intensity		C.U[2].	C.V[2].
	rev/s	s	mm/h	mm/s	-----%-------	
			ONE-NOZZLE UNIT			
1.0	N/A[3]	N/A	86.4	0.024	91.1	10.7
0.75	0.47	1.6/0.5	71.2	0.020	92.7	9.4
0.63	0.47	1.3/0.8	58.4	0.016	91.4	10.2
0.37	0.67	0.6/0.9	36.5	0.010	87.7	16.2
0.37	0.47	0.8/1.3	35.3	0.010	89.9	13.2
0.37	0.25	1.5/2.5	36.7	0.010	91.3	10.5
0.25	0.47	0.5/1.6	27.4	0.008	86.6	17.7
0.25	0.23	1.1/3.2	25.0	0.007	93.2	8.8
0.12	0.17	0.8/5.2	12.7	0.004	91.6	10.6
			THREE-NOZZLE UNIT			
1.0	N/A	N/A	115.8	0.032	85.8	19.2
0.67	0.33	2.0/1.0	84.9	0.024	86.7	17.2
0.33	0.33	1.0/2.0	43.2	0.012	85.7	17.8

[1]Fraction of cam circumference occupied by lobe, and therefore fraction of time solenoid switch is energized.
[2]Coefficients of uniformity and variation, respectively.
[3]Not applicable.

for most cams. Uniformities for the three nozzle field unit were approximately 85 %, the reduction probably due to spray overlap problems between nozzles. This value is still acceptable, and further refinements in nozzle orientation may improve the pattern somewhat.

A critical parameter associated with simulated rainfall is the kinetic energy of the drops produced, which must approximate natural rainfall as much as possible. Kinetic energies of the single nozzle unit were measured by collecting drops in an oil medium, photographing and then tallying drop sizes, and calculating energies, assuming terminal velocity of the drops. The results (Table 2) show energies in the range of 20-28 $J/m^2/mm$, which are typically associated with natural rainfall. The energies appear to be randomly distributed, with no high or low regions evident. These data were collected at 3 psi water pressure at the

Table 2. Kinetic energy ($J/m^2/mm$) of rainfall sampled *on* a m^2 plot under a single nozzle simulator (30 WSQ nozzle at 29 kPa).

22.5/ 19.2+	18.2/ 15.8		22.6
23.7/ 22.9	26.6/ 23.1		
24.0/ 20.2	28.1/ 21.1	25.1/ 26.8	24.9/ 24.5
		25.7/ 21.2	24.6/ 19.7
24.6		18.9/ 23.9	26.1/ 21.7

+Replicate values at same location.

nozzle; increases in pressure past 5 psi resulted in dramatic decreases in drop size and kinetic energy due to droplet break-up (data not shown).

B. Laboratory studies with rainfall simulator. The single nozzle simulator has been used to produce small pan data for a number of soils. Soil was loosely packed in 0.1 m by 0.3 m metal runoff pans, two of which were placed under the unit at once. Typically four rainfall events were applied to each set of pans: an initial "dry" run of 60 min, followed 24 hr later by three consecutive "wet" runs of 30 min, with 5 min periods between each. Runoff was collected in plastic flumes built into the front of each pan every 2-5 min. The volume of runoff was used to compute infiltration rate, and sand, silt, and clay analysis performed to determine soil loss.

Three sandy loam soils (Table 3) were treated with 5 mt/ha surface-applied phospho-gypsum, or left untreated, and data collected as described above. The application of gypsum had a significant effect on infiltration on each of the soils (Figs. 2-4). Infiltration at the end of the dry run was 2-4 times higher with gypsum, with runoff generally delayed for several minutes. For the Wedowee soil (Fig. 2), infiltration over the wet runs remained at about 1 cm/hr, more than twice the control. The Cecil soil (Fig. 4) showed a similar pattern, levelling out at 2.5 cm/hr. The Worsham soil (Fig. 3), a highly dispersive and poorly aggregated poorly

Table3. Selected properties of soils used in runoff/erosion experiments.

	Sand	Silt	Clay	Org. C.	pH	Cation Exch. Capacity	Exch. Na Percent.
	---------%	-------------				cmol(+)/kg	%
Cecil	75	17	8	1.2	6.3	3.15	1.2
Worsham	55	26	19	0.9	5.2	3.02	1.6
Wedowee	66	17	17	1.3	5.0	4.07	1.2

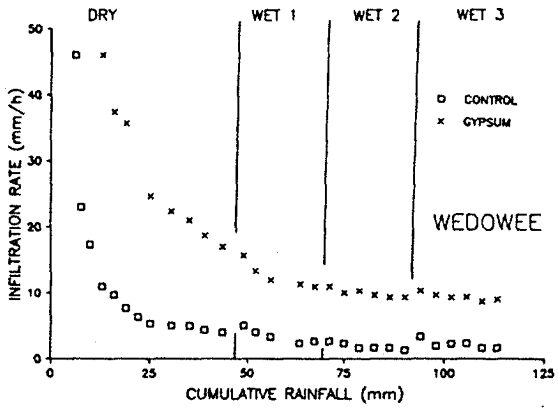

Figure 2. **Infiltration rates of control and gypsum-amended (5 mt/ha) Wedowee soil measured under single-nozzle simulator on 9% slope (intensity = 43 mm hr-1).**

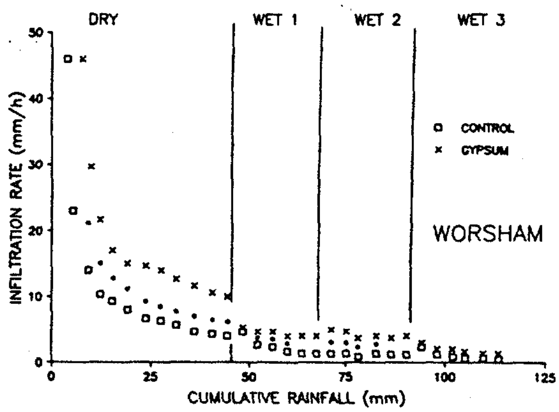

Figure 3. **Infiltration rates of control and gypsum-amended (5 mt/ha) Worsham soil measured under single-nozzle simulator on 9% slope (intensity = 45 mm hr-1).**

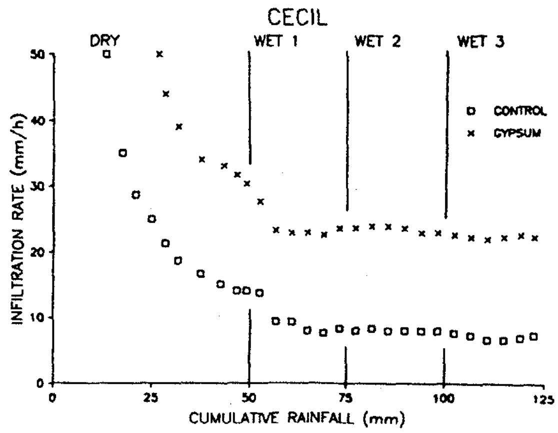

Figure 4. **Infiltration rates of control and gypsum-amended (5 mt/ha) Cecil soil measured under single-nozzle simulator on 9% slope (intensity = 53 mm hr-1).**

drained soil, did not maintain infiltration with gypsum above that of the control soil after the dry run.

Soil loss from these plots (Table 4) again showed a dramatic effect of gypsum application. Soil loss rates and total soil loss for the gypsum plots was half that of the control for the Wedowee. The same was true for the Worsham soil, despite the lack of infiltration response in the wet run discussed above. Evidently sediment transportability was sufficiently reduced by the gypsum (see below) to reduce soil movement off the plot, even though water transmission pores were sealed by the raindrop impact at the surface. The Cecil soil, which maintained the highest infiltration rate above control with gypsum, had the least response with respect to soil loss (Table 4). This soil is the sandiest of the three, and splashing of the soil was severe at this intensity (5 cm/hr). While higher infiltration was maintained with gypsum, splash transport of soil may have resulted in little treatment effect on soil loss.

The dynamics of the erosion/infiltration processes are revealed in an examination of the sediment concentrations and particle sizes of eroded sediments

Table 4. **Soil loss rates and total amounts from three soils with and without surface-applied gypsum (5 mt/ha).**

Run	WEDOWEE				WORSHAM				CECIL			
	Rate		Total		Rate		Total		Rate		Total	
	Cont.	Gyp.	Cont.	Gyp.	Cont.	Gyp.	Cont.	Gyp.	Cont.	Gyp.	Cont.	Gyp.
	$g/m^2/min$		kg/ha		$g/m^2/min$		kg/ha		$g/m^2/min$		kg/ha	
Dry	1.69	0.83	848	331	2.74	1.36	1562	775	0.55	0.23	317	126
Wet												
# 1	1.76	0.72	483	197	3.33	1.33	900	360	0.59	0.69	161	187
# 2	1.71	0.79	479	223	4.13	1.59	1114	428	0.57	0.49	157	133
# 3	1.62	0.76	480	212	4.16	1.83	1122	493	0.65	0.51	176	139
Sum			2290	963			4698	2056			811	585

(Table 5). For the Wedowee and Worsham soils, sediment concentrations in the runoff are roughly halved by gypsum treatment, particularly in the wet runs, and a major part of the clay in the gypsum sediment evidently is aggregated into the silt-sized category. This trend is not apparent in the Cecil soil, where sediment concentrations in gypsum-amended soil equal or exceed the control. The high sand content of the sediment of the Cecil supports the view that splash is a major contributor to soil loss, perhaps due to the action of gypsum in preventing compaction and surface hardening and thereby inducing higher splash losses.

As will be shown later, flocculation of the clay fraction of soil is probably the major mechanism whereby gypsum is effective in modifying soil behavior. This is likely to be largely an ionic strength effect, by which increases in solution ion

Table 5. Average concentrations and particle sizes of sediment eroded from untreated and gypsum-amended soils

Run	Untreated soil				Gypsum-amended+			
	Sed.*	Sand	Silt	Clay	Sed.*	Sand	Silt	Clay
	g/l	--------%--------			g/l	--------%--------		
			WEDOWEE					
Dry	3.21	12	54	34	2.96	17	83	0
Wet: 1	2.71	7	59	34	1.35	17	80	3
: 2	2.54	8	64	31	1.37	9	82	8
: 3	2.52	8	60	32	1.37	10	82	7
			WORSHAM					
Dry	4.67	12	61	26	3.59	14	84	2
Wet: 1	4.19	11	59	30	2.03	17	79	3
: 2	5.11	9	69	22	2.33	15	83	0
: 3	5.39	12	63	25	2.48	14	86	0
			CECIL					
Dry	1.30	33	51	16	1.94	38	53	9
Wet: 1	0.73	19	68	12	1.48	33	67	0
: 2	0.67	10	81	9	1.04	21	79	0
: 3	0.81	11	79	10	1.06	22	78	0

+5 mt ha-1 surface-applied

concentration allow clay particles to more easily approach each other and agglomerate (flocculate). The effect of gypsum amendment on electrical conductivities of runoff for the three soils is shown in Table 6. For untreated soil, the initial flush of salts from the soil upon wetting is quickly washed out by the rainfall, and final conductivities are extremely low. The electrolyte contents of these waters indicate concentrations < 1 mM/L, which will be shown to result in dispersion of clays for most of these soils. The gypsum treatment has the capacity to maintain roughly half-saturation of the runoff water, approximately 5 ***mM,*** which is adequate to flocculate the clay fraction. It is note-worthy that the Wedowee and Worsham soils show only limited decreases in conductivity after the four rainfall events, while the Cecil, with its high infiltration rate, is obviously becoming depleted of undissolved gypsum. It is clear from these results that the temporal effect of surface-applied gypsum is limited; however, it is evident that significant positive response may be expected for a duration equivalent to 10-15 cm rainfall. If the gypsum is applied at planting time on row-crop land, this may be

Table 6. **Electrical conductivities of runoff water from three soil with and without surface-applied gypsum.**

Run	WEDOWEE				WORSHAM				CECIL			
	Control		Gypsum		Control		Gypsum		Control		Gypsum	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	mS m-1											
Dry	5.8	1.2	108	112	6.0	1.1	150	152	9.0	1.3	110	102
Wet												
# 1	2.0	1.1	105	100	2.3	1.3	144	139	2.5	0.6	100	91
# 2	1.3	0.9	102	115	2.7	1.2	152	141	1.8	0.6	82	68
# 3	2.1	0.8	112	85	1.7	1.0	130	122	1.4	0.6	58	48

sufficient time for crops to emerge and develop a canopy, after which crusting and soil loss is significantly reduced.

An experiment similar to that described above was performed on the Greenville soil, a sandy clay loam Coastal Plain soil found near Plains, GA, that shows pronounced crusting in the field. Small-pan studies were conducted using unamended soil and gypsum-treated soil (5 mt/ha), and a treatment designed to simulate the effect of a dispersing agent, that being $NaNO_3$. Sodium compounds are added to soil as fertilizers, ‘and in manures and waste waters, and may result in exacerbation of dispersion and crusting problems. In this experiment $NaNO_3$ was added at 100 kg/ha (a common fertilizer rate) either alone or in combination with 5 mt/ha gypsum; the $NaNO_3$-treated soil was also treated with 5 mt/ha gypsum after it had been rained on, to test the effect of gypsum as a remedial treatment for Na-impacted soils.

The results from the Greenville soil experiments showed a significant effect of both gypsum and $NaNO_3$ compared to the control soil (Figure 6). The untreated control began to run-off at approximately 2 cm of applied rain, and reached an equilibrium infiltration rate of 1 cm/h; the gypsum-treated soil did not initiate runoff until 4 cm of rainfall, and maintained infiltration rates of >3 cm/h for the entire 12 cm of rainfall. The $NaNO_3$-treated soil sealed almost immediately, and infiltration rates of less than 0.5 cm/h were reached within a few minutes after rainfall initiation. When gypsum was added simultaneously with the $NaNO_3$, the Na had no effect, i.e., the infiltration curve was identical to the gypsum only treatment. When gypsum was applied after the rainfall event to the Na-treated soil and rain was reapplied, the soil behaved much like the control (Figure 6).

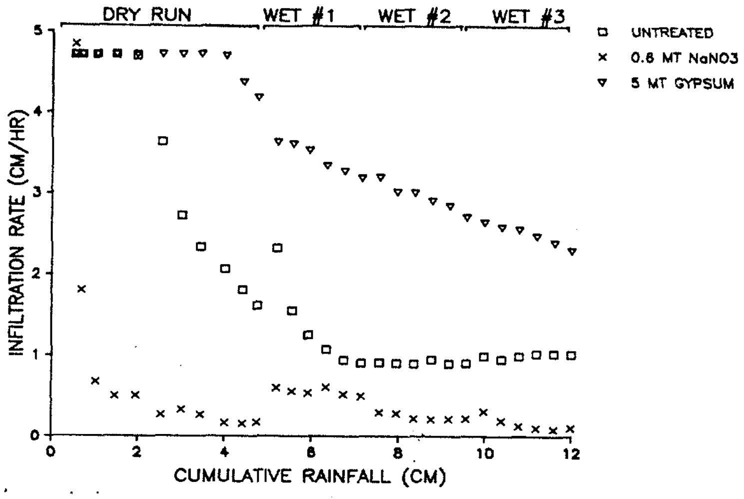

Figure 5. **Infiltration curves for Greenville soil amended with phosphogypsum and $NaNO_3$ compared to untreated soil (runoff pan studies, rainfall intensity = 48 mm/h).**

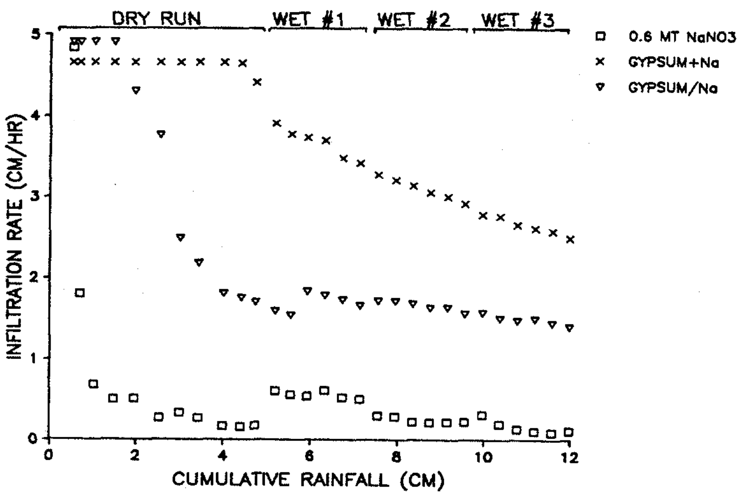

Figure 6. **Infiltration curves for Greenville soil amended with $NaNO_3$ in combination with phosphogypsum; "+Na"--applied simultaneously; "/Na"--gypsum applied after Na (pan studies, intensity = 48 mm/h).**

Soil loss data from these experiments closely parallel the infiltration data (Table 7): the Na-treated soil showed large increases in soil loss compared to the control, which was similar to the gypsum-after-Na treatment, while the gypsum alone and gypsum+Na (applied simultaneously) treatments had similar, low soil loss values. The clay content of the sediment is also closely correlated to both infiltration and soil loss trends for these treatments: added Na increased the proportion of clay in the sediment by a factor of 3-4 compared to the control, while addition of gypsum either eliminated or greatly reduced clay content in the sediment. These data are further confirmation of the important role of clay dispersion in runoff and erosion processes, supporting the contention that any factor increasing clay dispersion (e.g., Na additions) will increase runoff and erosion, and any factor promoting flocculation (gypsum additions) will decrease those processes. An important field use of phosphogypsum may be as an amendment to soils impacted by Na additions via waste waters, manures, canning waste, or Na-containing fertilizers, as a method of preventing deterioration of physical properties resulting from Na-induced dispersion.

Table 6. **Soil loss and sediment clay from $NaNO_3$- and gypsum-treated Greenville soil. (Letters indicated mean differences *via* LSD test.)**

	Dry Run		Wet Run #1		Wet Run #2		Wet Run #3	
Treatment	Soil loss	Clay	Soil loss	Clay	Soil loss	Clay	Soil loss	Clay
	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%
Untreated	200c	18b	211c	18b	279b	17b	249b	14b
$NaNO_3$	3560a	55a	480a	42a	820a	48a	1000a	49a
Gypsum	15c	0c	63d	2c	89c	0c	95c	3c
Na+gypsum	31c	0c	37d	2c	79c	0c	98c	3c
Gypsum after Na	470b	5c	330b	4c	320b	4c	320b	2c

Further clarification of the effect of applied gypsum was sought in an experiment to determine the specific effect of salt content in the applied rain- water on soil loss and infiltration. The longevity of the effect of gypsum on soil infiltration and erosion behavior seems to be closely linked to the increase in ionic strength (salt content) of the solution at the soil surface; in this series of experiments, water containing various levels of dissolved phosphogypsum was applied to two soils in small pans set at three slope gradients (9, 18, and 30%). The waters used for simulating the rainfall were deionized water (electrical conductivity (EC) = 0.2 mS/m), one-quarter saturated gypsum (EC = 50 mS/m), half-saturated gypsum (EC = 100 mS/m), and fully saturated gypsum (EC = 200 mS/m) solutions; the fully saturated solution contained about 2.5 g/L gypsum, with an ionic strength of 12.5 ***mM.*** Rainfall was applied for 1 h at 40 mm/h on soil that had been pre-wetted to field capacity. Three replicates of each soil/salt content/slope combination were performed.

The effect of applied rainwater ionic strength on the Appling (a sandy loam) and Davidson (clay loam texture) soil runoff rates is shown in Figure 7 at the three slopes investigated. As the gypsum content of the rainwater increased, there was a distinct effect on the Appling soil towards reducing the amount of runoff, as a percentage of the total rainfall applied. The major effect was between 0 and 500 umho/cm, with further little change as EC increased. For the Davidson soil, runoff tended to decline with increases in EC, but in a more gradual fashion. Slope effects on runoff percentage was minor. The soil loss results were somewhat more dramatic, as shown in Figure 8: both soils showed large decreases in soil erosion losses as ionic strength was increased from 0 to 500 umhos/cm. These decreases were particularly large at the higher slope gradients, especially at ***30%.*** Given the variation inherent in erosion measurements, no statistical

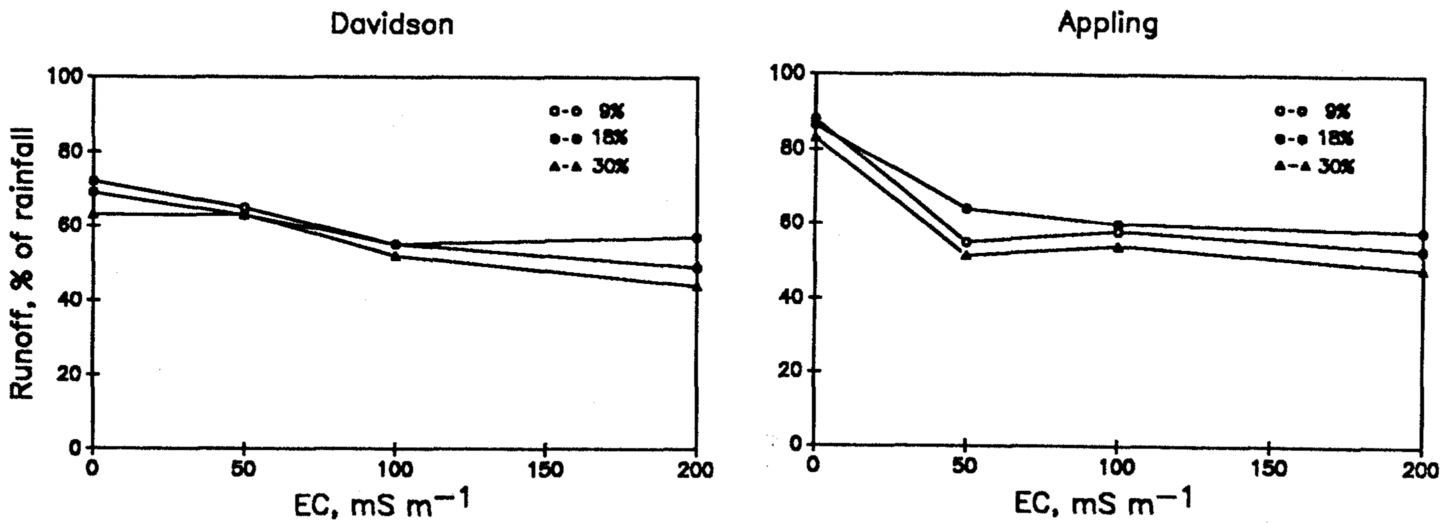

Figure 7. Runoff percentages for Appling and Davidson soil at three slopes as a function of ionic strength of rainfall (intensity=45 mm/h).

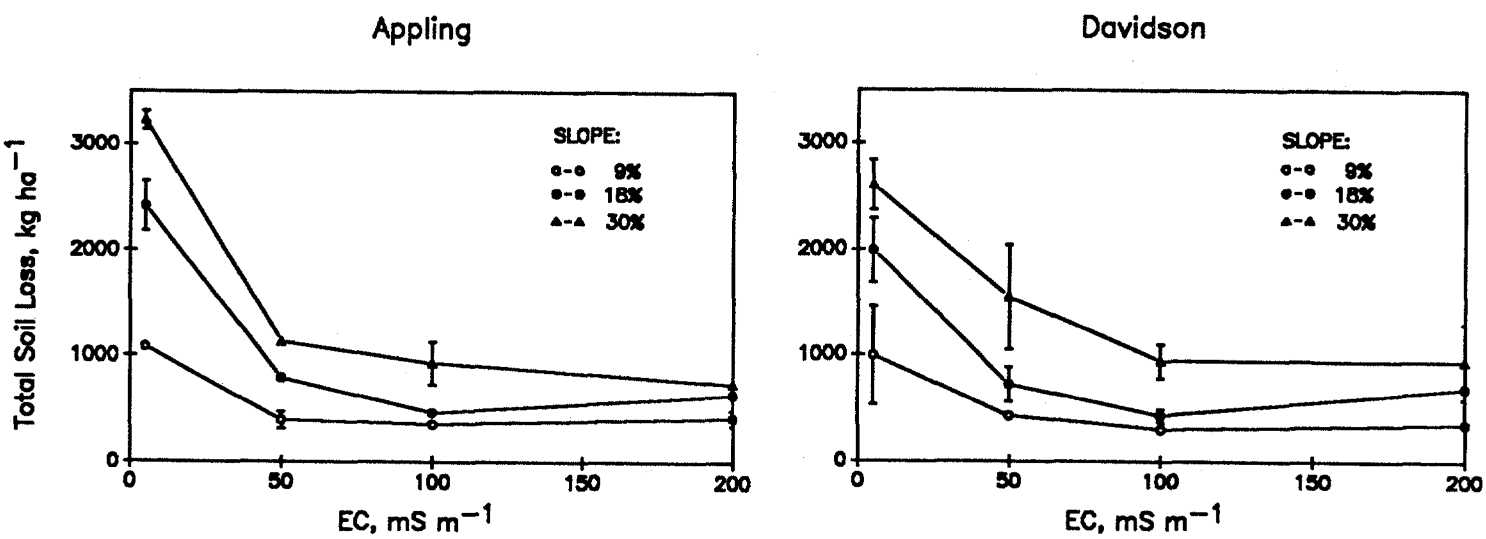

Figure 8. Soil loss of Davidson and Appling soils at three slopes as a function of ionic strength of applied rainfall (intensity=45 mm/h).

differences were detected in soil loss as EC was further increased to 1000 umhos/cm. Measurement of the amounts of dispersed clay in the sediment (data not presented) show that while the deionized water rainfall sediments were 10-20% primary clay, no clay was detected in the sediment collected from any of the rainfall treatments containing dissolved gypsum.

These results suggest that EC values of only 50 mS/m, or ionic strengths of roughly 3-4 ***mM,*** are sufficient to flocculate soil clays under rainfall conditions, resulting in some decreases in runoff and more significant reductions in soil erosion losses. The later effect is most likely due to lowered transportability of the sediments at the soil surface, due to coagulation of fine particles into larger aggregates. The magnitude of this phenomenon at high slope gradients suggests that gypsum amendment may be useful for slope stabilization in a variety of settings other than strictly agricultural, e.g., urban construction sites. The fact that only one-quarter saturation with respect to gypsum is sufficient to promote this effect indicates that the longevity of the effectiveness of gypsum application in the field may extend past the time of actual complete dissolution of the applied material, as residual salt is washed from the soil surface.

C. Field experiments with phosphogypsum. A field experiment was conducted over a one-year period in order to assess the effect of phosphogypsum amendment on runoff and erosion on an Appling sandy loam soil located at Watkinsville, GA Sixteen 1 m by 1 m plots were established in 4 blocks of 4 treatments each, with the plots bordered by steel enclosures with a runoff collection flume located on the downslope side. Phosphogypsum was surface-applied to the plots at rates of 0, 2, 4, or 6 mt/ha in the fall after wheat had been planted in the plots. Simulated rainfall was applied several times after planting using the 3-nozzle rainfall simulator, and runoff from natural rainfall events was also collected in barrels placed in the field and connected to the flumes with plastic piping. After wheat harvest the plot treatments were modified somewhat: two of the plots in each plot were tilled to a clean seedbed, and two were left with the wheat residue on the surface to simulate a no-till condition. Phosphogypsum was re-applied to one of the tilled and one of the untilled plots in each block at a rate of 6 mt/ha, while the other two plots were left untreated. Soybeans were planted by hand in the plots in June after the wheat had been harvested, and runoff from both simulated and natural rainfall events was collected over the summer growing season.

The results of a rainfall simulation performed on the plots immediately after wheat planting show that runoff rates were significantly affected by all rates of gypsum application (Figure 9). Higher rates of addition, up to 6 mt/ha, had progressively greater effects on reduction of runoff rate. Total runoff volume for the 6 mt/ha plot was approximately one-third of that of the control. Soil loss was reduced by similar or larger amounts (Figure 10): for the gypsum treatments, total soil loss was in the range of 100-230 kg/ha, while for the control (untreated) plots the value was approximately 700 kg/ha. Over the growing season, runoff and erosion was monitored from natural rainfall events, the volume of runoff water and sediment concentration being used to compute the cumulative infiltration, runoff, and soil loss from these plots. A total of nearly 500 mm of rainfall occurred on the plots over the wheat growing season of October to June. The runoff values from the plots over that time (Figure 11) show that the gypsum treatments were again effective in reducing runoff; runoff volumes were reduced approximately 50% by the 6 mt/ha rate compared to the control, while the 2 and 4 mt/ha rates gave intermediate runoff values. Soil loss on the wheat crop under natural rainfall showed nearly a 60% reduction with the highest gypsum treatment (Figure 12);

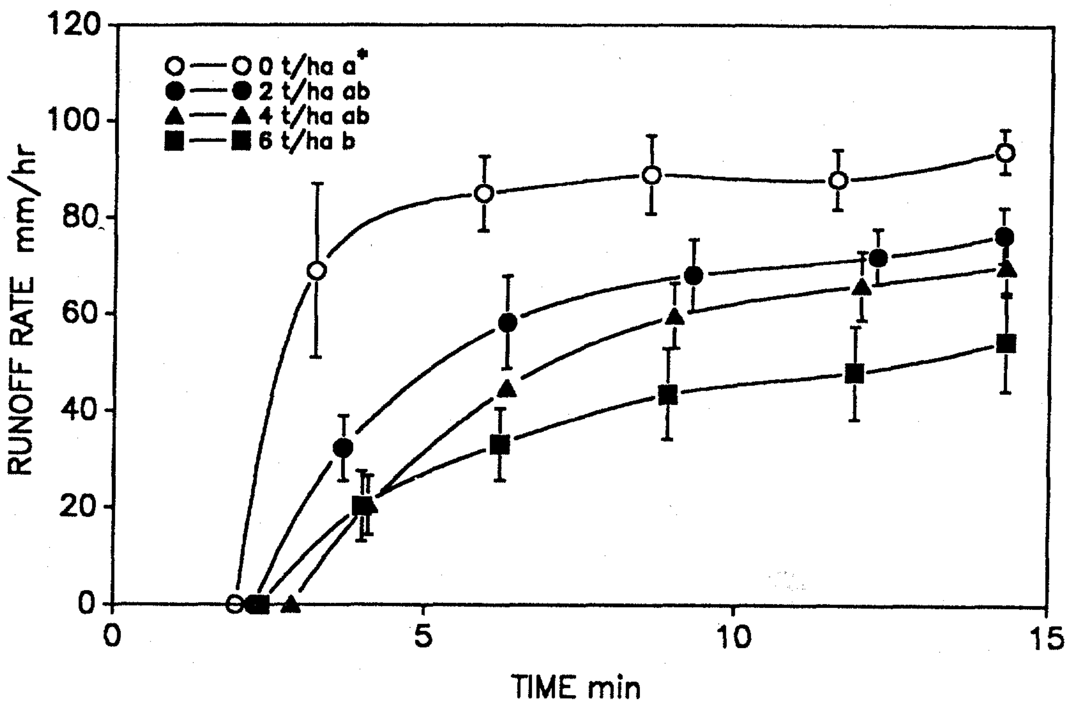

Figure 9. Runoff rate for field plots on Appling soil under simulated rainfall (90 mm/h intensity) as affected by four rates of phosphogypsum.

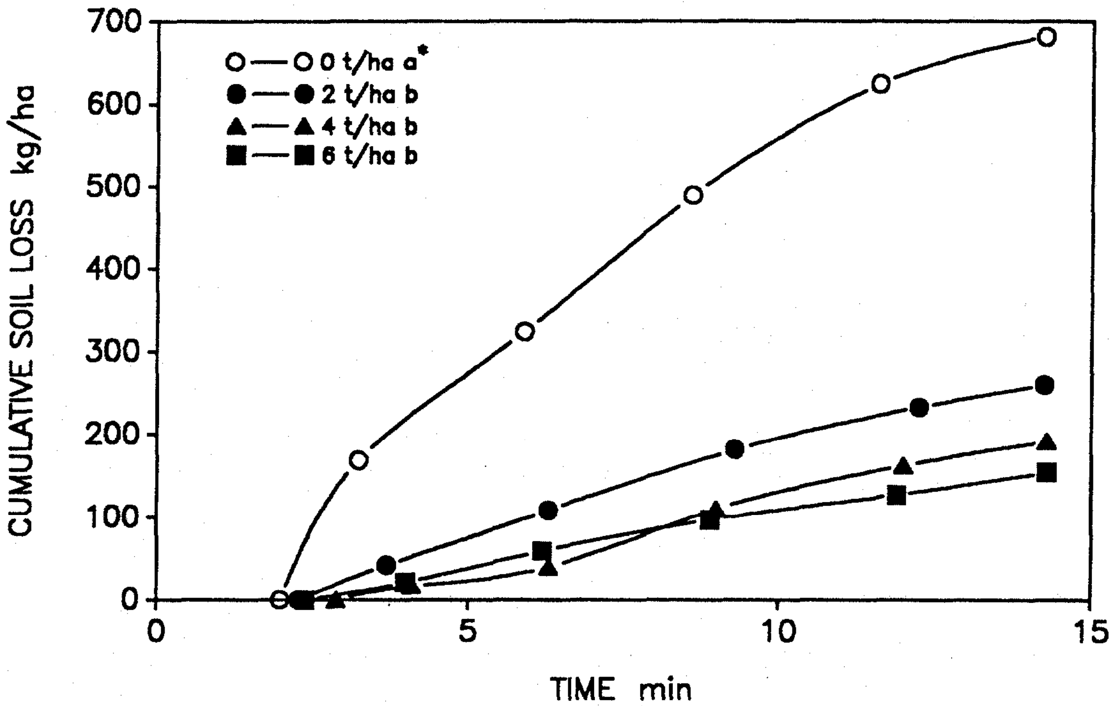

Figure 10. Soil loss for field plots on Appling soil under simulated rainfall (90 mm/h intensity) as affected by four rates of phosphogypsum. Letters indicate significant means differences *via* LSD test.

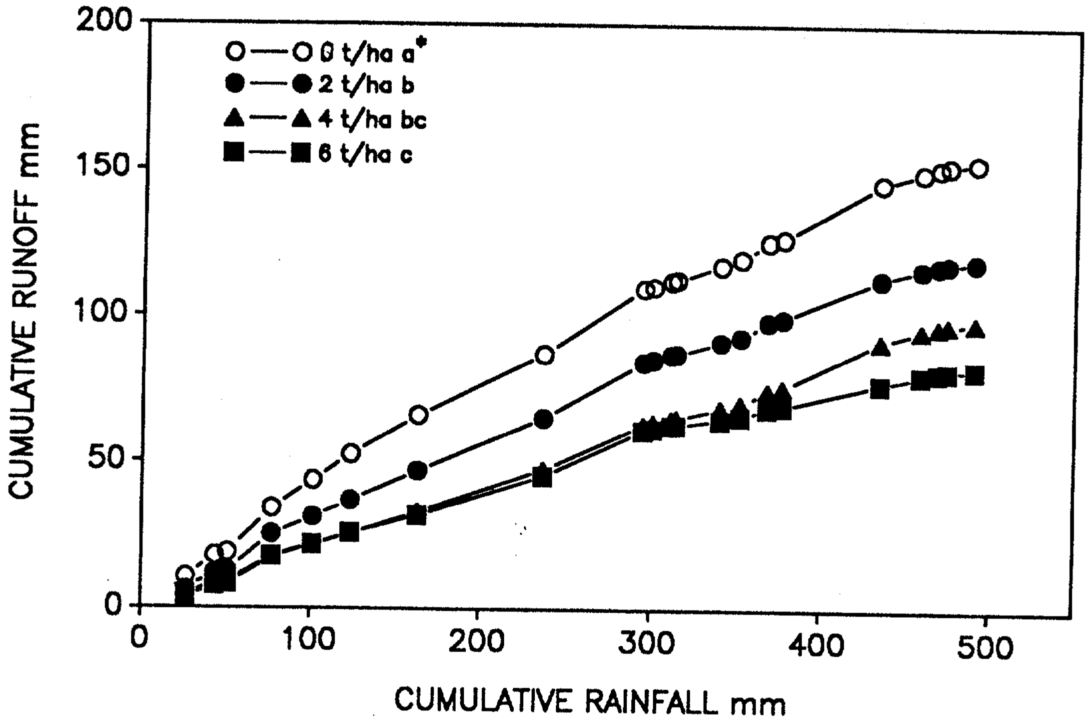

Figure *11.* Cumulative runoff over the winter growing season for wheat in field plots under natural rainfall as affected by four rates of gypsum.

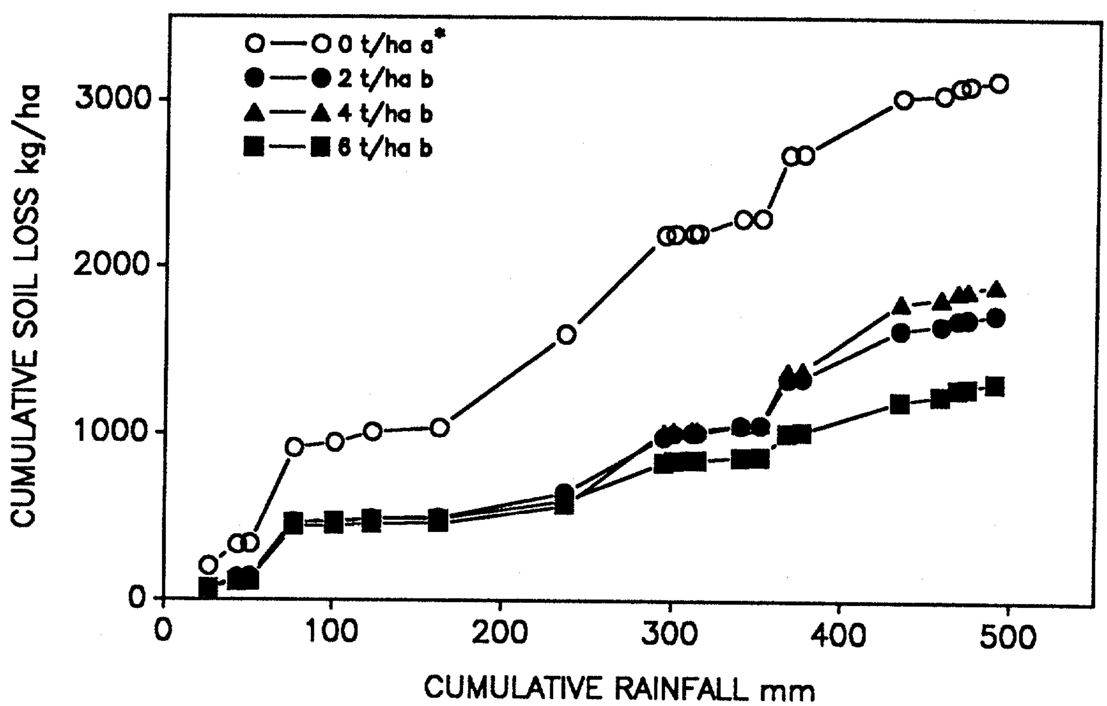

Figure 12. Cumulative soil loss over the winter growing season for wheat in field plots under natural rainfall as affected by four rates of gypsum.

however, the lower gypsum rates appeared to be proportionately more effective in soil loss reduction than in runoff reduction, as the 2 and 4 mt/ha gypsum rates had nearly as great an effect on soil loss as the highest rate.

After wheat harvest the plot treatments were split to evaluate the effect of gypsum in combination with surface residues on infiltration and soil loss. Two of the plots in each block were re-tilled, while two were left with wheat residue intact. Gypsum was reapplied at 6 mt/ha on one of the plots in each tillage split. The cumulative amount of runoff. from these plots over the summer growing season (June to November) showed a very large effect of the surface residue, but a lesser effect of the gypsum (Figure 13). Over the 420 mm of summer rainfall, runoff amounts to less than 50 mm on the residue-covered plots, with a small but non-significant effect of the gypsum in further lowering runoff. The effect of gypsum on the tilled plot was not nearly as significant as with the wheat; runoff was reduced only about 25 mm, out of a total of nearly 200 mm runoff. Soil loss from these plots (Figure 14) did indicate a larger gypsum response in the tilled plots, reducing growing-season erosion from 5600 to 4000 kg/ha. Residues were much more effective in soil loss reduction, regardless of the presence of applied phosphogypsum.

III. Effects of Gypsum on Soil Physical Properties

Given the fact that surface-applied phosphogypsum has an effect on soil water and erosive behavior in plot studies, it is important to attempt to understand the basic mechanisms of that effect in terms of which soil properties are involved. This information will be important in suggesting rates of gypsum addition for various soils, and in predicting which types of soils may benefit from gypsum amendment. The findings underscore the importance of clay fraction dispersion in

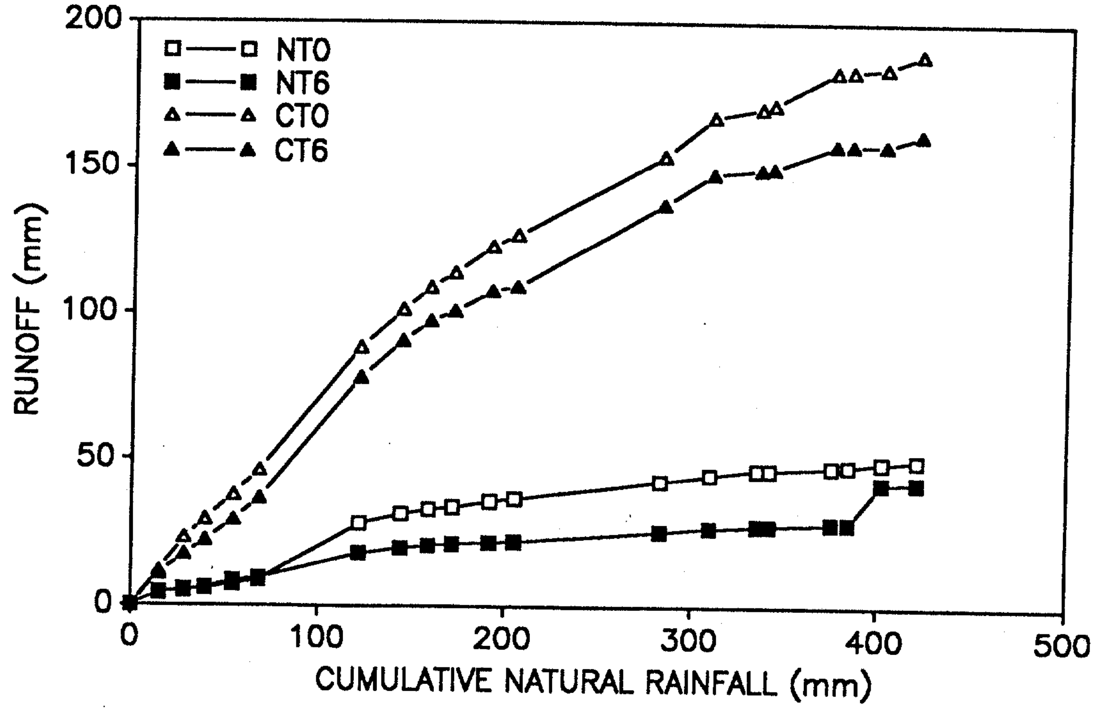

Figure 13. Effect of applied phosphogypsum and residue cover on runoff over the growing season under natural rainfall for field plots planted to soybeans (NT=no-till; CT=conventional tillage; O=no gypsum; 6=6mt/ha gyspum).

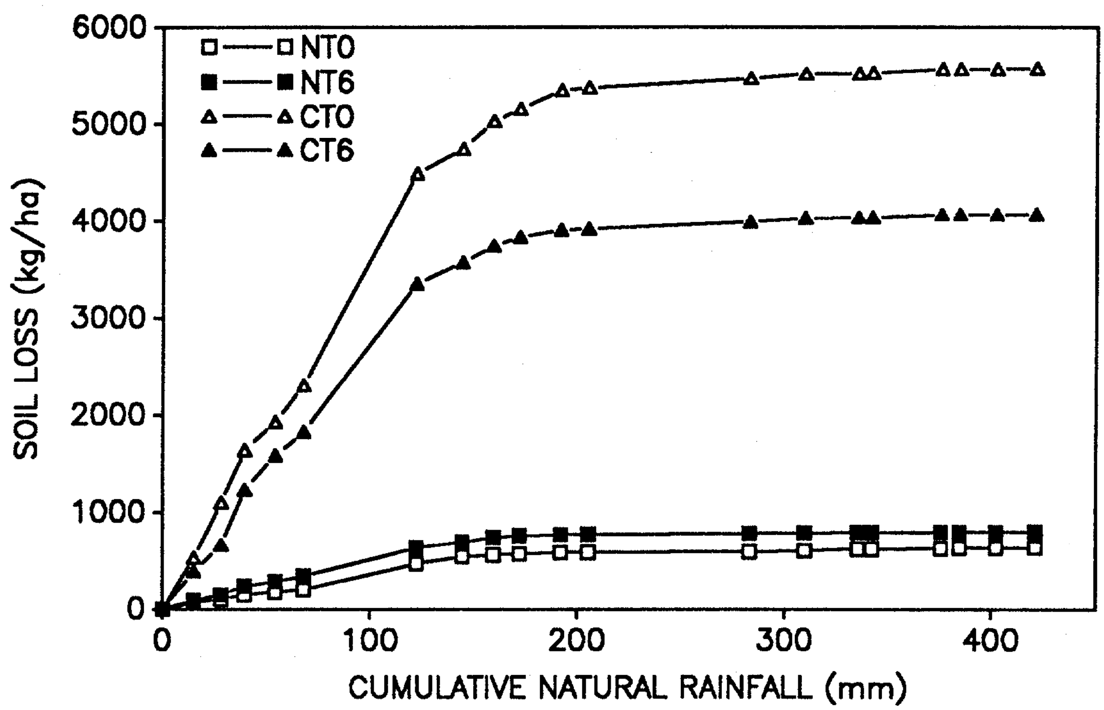

Figure 14. Effect of applied phosphogypsum and residue cover on soil loss over the growing season under natural rainfall for field plots planted to soybeans (NT=no-till; CT=conventional tillage; O=no gypsum; 6=6mt/ha gypsum).

soil erodibility and infiltration, providing an explanation of gypsum's observed effects. Preventing clay dispersion may become a major soil management goal as our understanding of this process evolves.

A. Factors affecting colloid dispersion. Traditionally dispersion has been studied in soils containing swelling clay minerals, and factors such as exchangeable sodium percentage (ESP) and electrolyte concentration have been identified as affecting the balance between particle attractive and repulsive forces and, hence, dispersion. Little study of kaolinitic soils, common in the Southeast, has been done in this regard. Experiments were therefore performed to assess the contributions of ESP, solution electrolyte concentration, and pH to colloid flocculation/dispersion using three typical southeastern topsoil clays.

Topsoils from the Davidson, Iredell, and Cecil series were used in a study, representing kaolintic/ oxidic, kaolinitic/smectitic, and kaolinitic/vermiculitic mineralogies, respectively. Clay fractions from each were adjusted to a range of ESP and pH levels, and equilibrated with varying concentrations of electrolyte solutions such that the SAR (sodium adsorption ratio) of the solution matched the ESP of the clay sample. After allowing for flocculated particles to settle overnight, the solution turbidity (amount of suspended clay) was determined optically and plotted vs. salt concentration for each soil/SAR/pH combination. The salt concentration at which 50% of the clay had flocculated was read from the plot as the critical flocculation concentration for that treatment. The results (Table 8) show a marked dependence of the salt concentration required for flocculation upon both pH and SAR for each of the soils. At low pH the soils possess only low amounts of charge, are unable to repell each other, and hence flocculate. At higher pH variable charge development causes increased repulsive forces and dispersion. This is particularly true in the Davidson soil, which required 8

Table 8. Critical flocculation concentrations for clays from three Georgia soils as a function of pH and sodium adsorption ratio (SAR).

SAR	pH 4	pH 5	pH 6	pH 7	pH 8
	--------	--------	mM(+)/L	--------	--------
			CECIL Ap		
0	<0.1	0.5	1.0	2.2	2.8
2	<0.3	1.4	3.5	4.3	ND
4	<0.3	ND	4.5	6.3	7.4
8	<0.8	3.9	6.9	10.2	11.8
16	<2.0	4.2	10.0	16.7	19.2
			DAVIDSON Ap		
0	<0.1	4.0	6.8	8.0	7.4
2	0.2	7.0	7.7	9.2	8.8
4	<0.3	7.8	10.5	11.2	10.8
8	<0.8	13.4	22.6	21.7	23.7
16	<2.0	20.1	40.8	40.5	40.4
			IREDELL Ap		
0	0.05	1.0	3.2	4.9	4.6
2	0.90	3.8	4.3	5.6	5.2
4	1.10	4.3	7.6	7.8	7.6
8	2.40	7.9	12.5	13.0	14.0
16	3.30	11.0	17.7	29.0	29.7

mM/L at pH 7 and SAR = 0 for flocculation, compared to 4.9 for Iredell and 2.2 for Cecil. The effect of increasing SAR was nearly as important as pH, as even low amounts of Na present in the system (2-4 %) resulted in significantly greater salt concentrations required for flocculation. Many southeastern soils contain Na in this range, and have pH's in the range of 5-7, indicating that under such conditions salt levels of 3-10 mM/L would be required for flocculation.

B. Hydraulic conductivity and dispersion. A series of experiments was designed to determine the effect of electrolyte concentration, pH, and Na level (SAR) on water flow rates through repacked soil columns of the three soils studied in the above-described dispersion experiments. Columns (4 cm radius, 7 cm tall) of soil pre-adjusted to selected pH levels were leached with concentrated solutions of fixed SAR, which were then replaced with more dilute solutions. Ten pore volumes of dilute solution were passed through the columns, and the final conductivities compared to the initial flow rates, yielding a relative conductivity for that soil/pH/SAR treatment.

The results obtained mirrored to a large degree those of the dispersion experiments, in that increasing Na level and decreasing concentration resulted in a deterioration of soil physical properties, in this case, water conductivity (Figure 15). These effects were most in evidence in the Iredell soil, where the effect of increasing Na reduced conductivity to near 0. The Cecil soil showed a stronger dependence on electrolyte concentration, with SAR as a factor only at higher salt levels. The combined effect of the two variables influenced conductivity of the Davidson soil only at the highest SAR and lowest electrolyte level. Taken together, these data indicate that low levels of exchangeable Na coupled with low solution ionic strengths are major factors contributing to poor physical properties of these soils. Other experiments with these soils (data not presented) show decreased conductivity with increasing pH, again corroberating the dispersion data.

The definite link between clay dispersion and water flow rate is established in Fig. 16, where relative conductivity is plotted against turbidity measured in the percolate solutions collected in the conductivity experiments. The relationship between these variables suggests a direct influence of clay dispersion (as measured by turbidity) on hydraulic conductivity, most likely operating by the action of dispersed clay in clogging macro-pores within the soil matrix and thereby reducing flow through these larger pores. Thus it is likely that the observed effects of gypsum in increasing infiltration in the field experiments are a direct result of flocculation and pore stabilization evidenced in these studies.

One complicating factor is apparent in comparing the conductivity data with the dispersion results of Table 7, that being the dissimilar relative effects of Na and electrolyte on the three soils (i.e., Davidson is the most difficult soil to

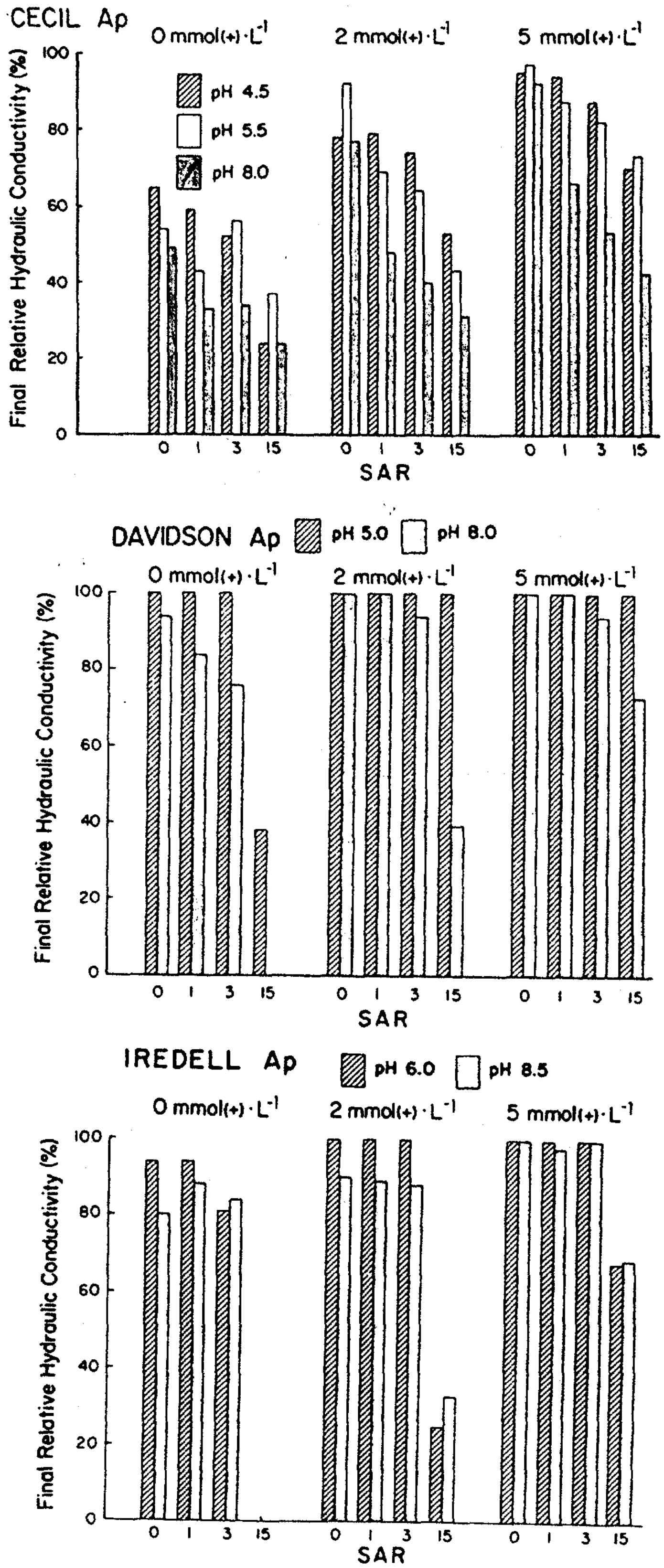

Figure 15. **Final relative hydraulic conductivity of Cecil, Davidson, and Iredell soils as a function of salt concentration, SAR, and pH.**

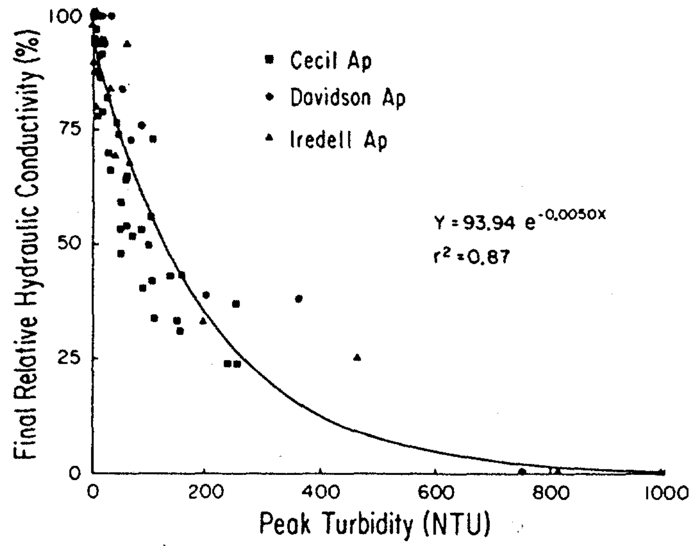

Figure 16. **Relationship between peak turbidity of percolate solutions and final hydraulic conductivity for three soils.**

flocculate, but has the highest overall relative conductivity). Other preliminary experiments have shown a significant effect of the ratio of solution phase to solid phase in determining dispersion, that being a greater tendency to disperse as greater relative amounts of solution are added. The ability of a soil to release salt to solution, thereby maintaining sufficient salt for flocculation, may be involved. Initial studies reported in the next section have begun to address this question, and will hopefully bring dispersion data more closely in line with other measured physical properties.

C. Flocculation of soil clays by gypsum. A series of experiments was initiated with the dual objectives of determining soil properties influencing clay dispersion in field soils, and of assessing the effects of added phosphogypsum levels on dispersible clay. Two solution:soil ratios and four levels of solution gypsum saturation were used on eight topsoils, with 24 hr shaking time, after which the proportion of clay remaining in suspension was determined. In Figure 17 are shown some representative results for 8 soils at one (20:l) solution:soil ratio; a range in behavior in these soils was observed, from quite highly dispersed to nearly completely flocculated in their field state. The Dyke and Altavista soils, for example, dispersed appreciably only in pure water at the wider solution:soil ratio, while the Worsham and Wedowee soils were highly dispersed at the lower electrolyte levels. For most of the soils used, the lower (8:l) ratio resulted in a higher percentage of clay dispersed at low gypsum levels (data not shown), but as gypsum was added (up to 10% solution saturation) this lower ratio flocculated to a greater degree than the 20:l ratio. This may be a result of greater abrasion at the lower ratio, causing more dispersion in dilute solution, but resulting in higher ionic strengths at higher gypsum levels, and eventually causing flocculation. An

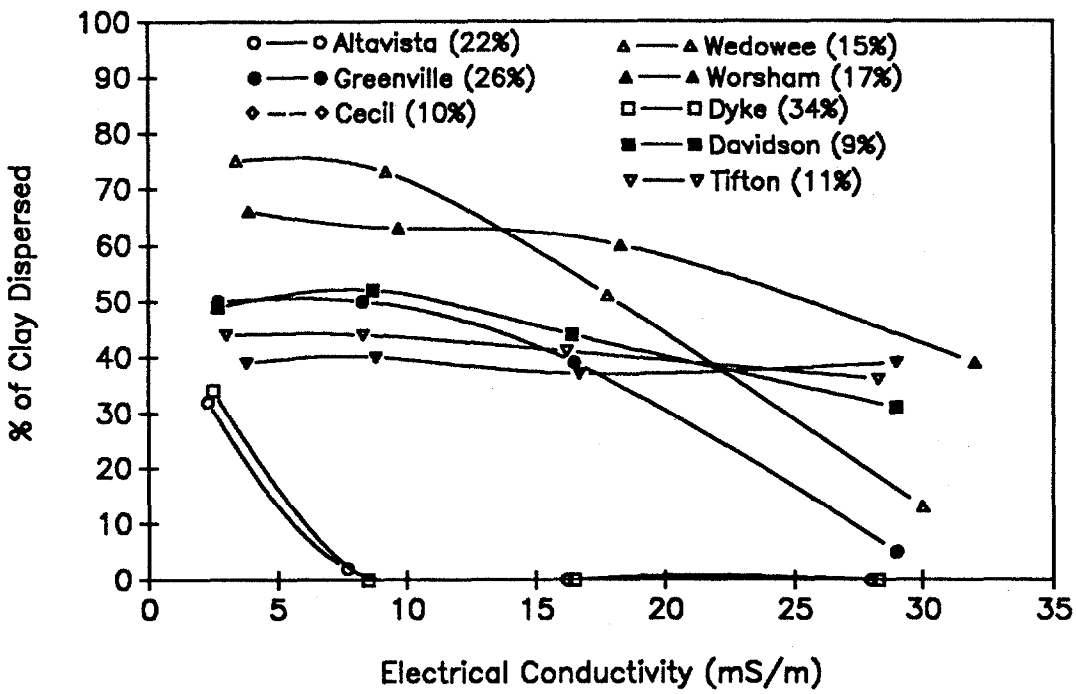

Figure 17. **Clay dispersion of eight Georgia soils as influenced by salt additions (via phosphogypsum); 20:l solution:soil ratio, shaken 16 h. (Clay percentages of original soils shown in parentheses in legend.)**

important point is that only 10% solution saturation with respect to phosphogypsum is sufficient to flocculate 2 of the 6 dispersive soils, and reduce dispersion significantly in 2 others. It is apparent from the initial ionic strengths in Figure 17 that the amounts of salt released by the soils themselves are low compared to even a 10% gypsum solution, and differences between the soils are minimal.

D. Crusting and seedling germination studies. A potentially important effect of soil crusting in the field is crusting-induced inhibition of seedling emergence in the field. Conditions which favor formation of hard-setting crusts appear to be quite specific and to a large degree unknown; informal observations suggest high-intensity rainfall immediately after planting, followed by rapid drying under high solar radiation input are optimum for crust formation that may inhibit emergence. Experiments in a laboratory setting designed to simulate these conditions were unable to produce adequately hard-setting crusts, and subsequent measurement of the effect of gypsum on crusting was not possible. Field research was therefore undertaken to attempt to show the effect of surface-applied phosphogypsum on seedling emergence.

An initial experiment was conducted on the Plant Science Farm in Watkinsville, GA, on a Cecil sandy loam using two varieties of soybean. Natural rainfall did not occur, and irrigation water (20 mm) was applied to the plots, which were arranged in four blocks each containing 5 levels of applied gypsum. Measured amounts of applied water showed poor distribution of the applied water, which varied from 12 to 28 mm. The emergence results (Table 9) were highly variable, evidently due to the variation in applied water. No treatment effect was observed after statistical analysis of this data. A second experiment was established on a Norfolk sandy loam soil in the Coastal Plain region, with 2 mt/ha gypsum applied

Table 9. **Effect of applied phosphogypsum on soybean emergence in field experiments using Wright and Duo-Crop cultivars.**

Cultivar	Phosphogypsum rate (mt/ha)					
	0	0.5	1.0	2.0	4.0	8.0
	% emergence					
Wright	44	76	19	50	36	37
Duo-Crop	17	12	30	24	37	35

in a band over planted cotton seed. Four blocks were established with a treated and untreated row sections included. Eighteen mm of irrigation water was applied, with acceptable variation in this instance (15-22 mm range). Emergence of cotton was monitored over 12 d, during which a typical hard-setting crust developed at the soil surface. The results for phosphogypsum-treated and untreated rows given in Table 10. Gypsum treatment had a significant early effect on emergence with cotton on this soil, with nearly doubled plant emergence during the first 5 days after planting. Some effect was still evident after 12 d, at which time no further increase in emergence was observed on either treatment. Whether the increase noted here (from 68 to 79%) is significant from the grower's point of view is uncertain; in this case emergence on untreated plots was probably adequate. More studies are needed under more controlled conditions in order to establish the importance of this effect.

Table 10. **Effect of 2 mt/ha phosphogypsum banded over the row on cotton emergence on a Norfolk sandy loam (means of 4 3-m rows).**

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

E. Effect of gypsum on phosphatic clays. Given the efficiency of gypsum as a flocculant of colloidal particles, this material may well be useful in clarifying and/or dewatering natural waters or other waste suspensions containing dispersed clay. The use of phosphogypsum on waste phosphatic clays derived from phosphate rock processing was suggested as a possible area of investigation by FIPR personel. Samples were obtained from FIPR, in the form of 45% solids pastes, containing greater than 95% fine particles with a pH of approximately 7.5. An experiment was performed by diluting samples of the paste with gypsum solutions ranging from 0 to 100 % saturation to various suspension solids concentrations. The solids content of the suspensions prepared ranged from 23 to 7%, wt/vol. The suspensions were equilibrated 48 hrs and centrifuged for various times to simulate natural settling. The volumes of flocculated clay were measured after centrifugation, and floc densities (g 100/ml) calculated.

The major feature apparent in the data collected (Table 11) is that the phosphatic clay studied was quite well flocculated in its untreated state, and at the higher solids contents gypsum had no effect on the density of the floc. Diluting the suspensions obviously decreased floc density, as did decreasing centrifugation time.

Table 11. Floc density *of* phosphatic clay as a function of solution gypsum saturation and percent solids.

Suspension solids	Centrifuge* time	% gypsum saturation of solution				
		0	10	25	50	100
% wt	min	----floc density: g/100 ml------				
23.0	3	33	33	34	34	33
12.5	3	16	16	16	16	17
	8	22	23	23	23	24
9.4	3	12.5	13.2	13.6	13.9	14.5
	8	19.8	20.8	21.5	22.1	22.8
7.0	3	9.4	10.6	11.1	11.3	12.0
	8	17.6	19.4	20.1	20.1	22.6

*IEC floor model, 1800 rev/min

Only below approximately 10% solids did added gypsum act to increase the density of the floc, acting as a dewatering agent by increasing the amount of clay per unit volume of suspension. Further dilution of the solids was found to result in actual dispersion only below approximately 2% solids. Thus, a preliminary conclusion drawn from this experiment would suggest that gypsum addition is unlikely to significantly affect the properties of phosphatic clays, as these clays are already flocculated. Their high affinity for water is undoubtedly a result of a smectitic mineralogy, which salt addition on the order of gypsum saturation is unlikely to alter to any degree.

IV. Mechanisms Responsible for Gypsum Effects

A great deal of the above discussion has referred to the possible mechanisms by which gypsum may affect the physical and chemical properties of soils, and thereby favorably modify their behavior in the field setting. In this section these relationships will be further discussed, and some conclusions reached, however preliminary given the relatively small body of data presented here, on the potential for use of phosphogypsum on highly weathered soils in a crop production setting.

A. Soil chemical properties and dispersion. The underlying connection between soil chemical properties and the physical behavior of soil in the field has been recognized for some time, but is often difficult to demonstrate. An important example is the relationship between the amount of easily dispersible clay, essentially a chemically controlled property, and soil loss measured on small runoff pans (Fig. 18). The study from which this data are derived also demonstrated a significant correlation between dispersible clay and infiltration rate. These findings are fully compatable with the results presented in this report, and

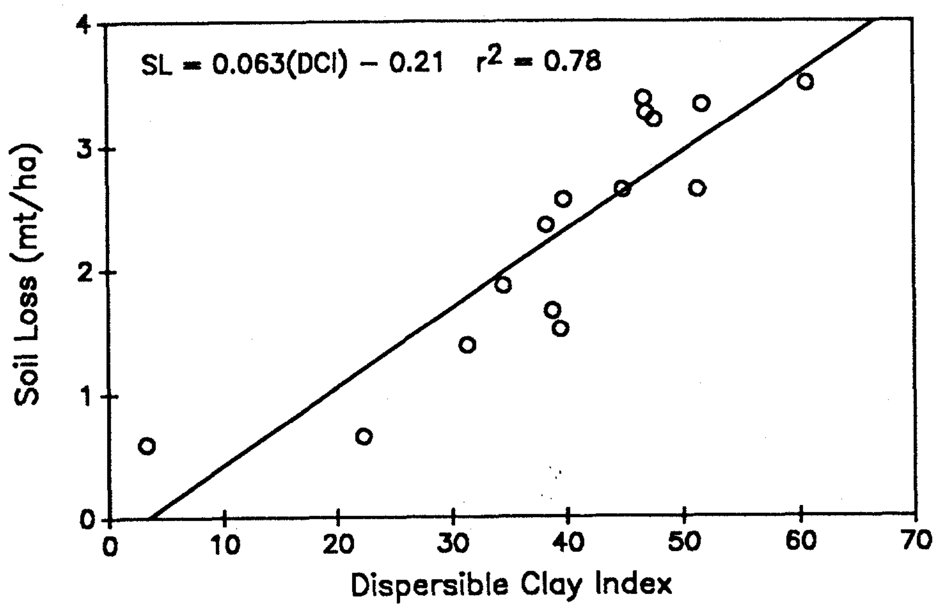

Figure 18. **Relationship between dispersible clay (as % of total soil clay) and soil loss as measured in small pan% (I=65 mm/h) on 15 Georgia soils.**

further emphasize the importance of soil chemical processes in regulating the physical behavior of soil. The capacity of added gypsum to increase solution ionic strength and to displace exchangeable Na, thereby enhancing clay flocculation, ensures that it will have at least a short-term effect on water infiltration and soil loss. Laboratory studies described here have so far shown that ESP, ionic strength, and pH are important variables in determining clay dispersion and conductivity of southeastern soils, and suggest that gypsum application probably affects soil physical properties and conductivities through modification of ionic stength and, to a lesser degree, ESP. Our understanding of the dispersion potential of various soils is less than complete, however, and further examination of dispersibility of topsoil clays should continue. Specific-ally, the importance of salt release as a factor in dispersion needs further study, as this factor may provide a key in screening soils that will be gypsum-responsive in the field. The ability to test for gypsum response in the laboratory is crucial, as field plot work is far too laborious to evaluate gypsum on more than a limited number of soils. The development of a simple laboratory test, similar to the dispersion measurements made in Figure 17, may enable such a screening, although more field work is necessary to calibrate such a test.

While the "gypsum effect" on highly weathered soils has been well documented in the studies reported herein, a generally wider range of soils should be investigated. The initial assumption of this study, that only highly weathered, low-salt-releasing soils will respond, needs to be realistically tested. And even within the highly weathered soil group, longer-term studies need to more fully establish the time period over which surface-applied gypsum is active in the field.

B. Longevity of the gypsum effect. A major question that will affect the feasiblity of wide-spread field use of phosphogypsum is the longevity of this effect, and the optimal application methods to enhance the duration of the effect. Dr. M. Sumner in a related project (FIRP 83-0l-024R) has discovered serious cation imbalances that result from heavy gypsum applications to some sandy soils, which suggests that more frequent small additions may be more efficacious. This approach is likely to result in more gypsum being present at the soil surface over time, and might be expected to improve water relations and decrease soil loss to a greater degree than one large single application. The results of our field study reported here would seem to support such an approach: the effect of 2 mt/ha vs. 6 mt/ha in the wheat experiment (Figures 11 and 12) were quite similar. Rates of l-2 mt/ha applied annually over a period of years would improve water status through greater infiltration, and significantly reduce erosion. The lesser magnitude of soil loss and runoff reductions in the soybean experiment (Figures 13 and 14) may be due to the extreme dryness of the summer season (1988) during which the experiment was conducted; the typical high-intensity storms did not occur as frequently, and overall rainfall was erratic. These and other results suggest the effect of rainfall intensity on the soil response to gypsum also deserves further study in order to assign some probabilities on which weather conditions might be expected to promote or hinder positive infiltration/erosion responses to gypsum.

C. Prospects for use of phosphogypsum. The probability that growers and farm managers will adopt a new practice or soil amendment is determined largely by economic forces, although many other factors may enter into such a decision. Evaluating the economic balance of phosphogypsum use is obviously closely tied to farm prices, gypsum costs, and expected yield increases from the gypsum. The objectives of this project did not include extensive yield measurements; Dr. Sumner's (FIRP 38-0l-024R) related project has accomplished this on a variety of crops, with rather convincing results: in many cases yield increases of 20-40% or higher are more than adequate to offset the cost of 1-2 mt/ha of phosphogypsum per year. If the cost of the by-product gypsum remains in the range of $30-40/ton, it seems likely that growers will adopt this technology. The time frame of such adoption will necessarily be gradual; extension publications and meetings, farm publications, and word of mouth are the major mechanisms by which information on new prac-tices reaches the end-user, and as such a reasonable time period is required for this dissemination.

A secondary impetus for adoption of this new technology may be the Food Security Act, which mandates that soil erosion levels be controlled within certain tolerances on farms which participate in governmental programs. The demonstrated capacity of phosphogypsum to reduce soil erosion may prove a valuable managment strategy for farmers cultivating lands that otherwise may not be able to meet soil loss tolerances.

Every effort has been made on the part of investigators and cooperators on this project to communicate with extension personnel, farm groups and the farm press, and individual farmers regarding the potential use of gypsum. It is, in most respects, up to the marketplace to judge the usefulness of this material based on its performance in a production setting.

V. Literature Cited

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OVERALL PROJECT CONCLUSIONS

The most general conclusion of the research reported herein is that by-product phosphogypsum is effective in reducing runoff rates and soil loss from high-intensity rainfall on highly weathered soils. The mechanism for this effect is largely an ionic strength effect, whereby the clay fraction of the soil is flocculated by the salt released via dissolution of gypsum at the soil surface during rainfall. This flocculation prevents surface sealing, which seems to be promoted by the presence of de-flocculated clay at the soil surface, and thereby maintains higher infiltration rates. Gypsum is even more effective in reducing soil loss, presumably by both reducing runoff volumes and velocities and by inhibiting detachment of erodible soil particles by the flocculation mechanism.

Laboratory experiments predict that most southeastern soils will be readily flocculated by salt concentration of only 100-300 umhos/cm of gypsum, amounting to roughly 1-2 mM salt or less than one-quarter saturated solutions. Thus, field-applied gypsum should remain effective as long as this level of salt can be maintained by dissolution. Field tests on wheat and soybeans confirmed that runoff and erosion were reduced in similar degree to that shown in small pan studies for the duration of the growing season. Longer term tests need to be performed to demonstrate the exact extent of this duration. However, given the need for annual tillage and the desirability of applying small amounts of gypsum annually (as demonstrated in soil fertility studies), it appears that a general preliminary recommendation of l-2 mt/ha might be made for phosphogypsum application to rowcrops for the purpose of ameliorating soil physical properties and promoting better water relations.

APPENDIX: Publications Resulting from this Project

Chiang, S. C., W. P. Miller, and D. E. Radcliffe. 1985. Hydraulic conductivity of southeastern soils as affected by cation type, concentration, and pH. ***Agron Abstr.,*** 139.

Newman, K. D., and W. P. Miller. 1985. Dispersion of southeastern soil clays as a function of electrolyte and pH. ***Agron. Abstr.,*** 150.

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