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Effect of Drilling Fluid Components and Mixtures on Plants and Soils

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EFFECT OF DRILLING FLUID COMPONENTS AND MIXTURES ON PLANTS AND SOILS

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

ABSTRACT

Effect of Drilling Fluid Components and

Mixtures on Plants and Soils

by

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Utah State University, 1977

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The concern about the environment has required that the effects of drilling fluids (muds) on surrounding areas be known. This study was initiated to investigate the effects of various muds on plant growth and on soils.

In preliminary studies in Phase I (31 individual mud components), it was concluded that the obvious dominant effects on plant growth of detrimental drilling fluid components included excess soluble salts, excess exchangeable sodium percentage, possibly a high pH in some mixtures, and undesirable physical conditions. The latter resulted from the sodium and/or starch, gums, and bentonite.

Phase II, the second year's study of the effect of drilling fluid on six soils and on the plant growth (which is this report) was designed to use seven typical drilling fluids at ratios of 1:4 (called the low rate), and 1:1 (called the high rate) by volume of liquid mud to disturbed and settled soils using green beans and sweet corn as the test plants. The seven mud mixtures were potassium chloride mud (PCM), diesel oil emulsion mud (DOEM), high pH lime mud (HPLM), lignite lignosulfonate sodium mud (LLSM), lignite lignosulfonate potassium mud (LLPM), dichromate mud (DTM), and a mud base (MB). Each mud contained bentonite and barite plus sodium or potassium hydroxide plus a few other substances.

Too much soluble salts or too high an exchangeable sodium percentage was the major cause of reduced plant growth. The dispersing problem of mud-treated soils caused by high exchangeable sodium percentages results from the high sodium hydroxide contents added to the muds.

Early attempts at leaching the soils with tap water were unsuccessful because of low permeability. Releaching all samples finally with salty water, first with 1 percent $Ca(NO_3)_2$, and later with 0.2 percent $Ca(NO_3)_2$, and finally with tap water was effective and plant growth improved in all mud mixtures.

In unleached treatments the muds PCM, DOEM, and DTM were most limiting to plants growth.

Reclamation of soils into which drilling fluids (muds) are mixed seems to require primarily (1) the removal of excess salts, and (2) a lowering of the content of exchangeable sodium with some additions of chemical amendments (calcium salts) and adequate leaching.

(147 pages)

INTRODUCTION

Petroleum is essential in today's world. However, in our increasingly crowded world, the impact on the environment of wastes and refuse must also be considered.

In well-drilling operations by the rotary method, a fluid is maintained in the hole at all times. During actual drilling the fluid is circulated continuously to remove cuttings. The floating out of the cuttings from the hole is aided if the fluid has a viscosity greater than that of water. Viscosities of the order of 15 centipoises are about the usual norm of good drilling practice (Baroid, 1954; Grim, 1962).

The drilling fluid (mud) carries out rock fragments which are sieved out and deposited in a pit; most of the screened mud is recovered and recycled many times through the hole. During the drilling period, a pond is used to accumulate the drilling wastes, some non-recoverable mud, various other wastes such as spilled oils, and any other washings from the drilling rig. These materials may be later buried or spread over an area and disced into the soil. The effect of these materials on the growth of plants is largely unknown (see Figure 1).

The relatively small areas covered by these "waste reservoirs" and discarded muds have, in the past, minimized public interest about their localized effects on soils and plants. However, increased concern about all environmental pollution and the continuance of well drilling makes it essential to evaluate any harmful effects of the drilling muds on the disposal area and its ecology. If harmful effects exist, they need to be studied. Therefore this project was initiated to study some of the problems associated with the use of drilling muds. Until this project began there was almost no information on the effect of drilling muds on plant growth or on soil properties. These effects also need to be narrowed down to the individual mud components causing the problems.

Thus, this study was undertaken to determine possible effects of drilling muds on plant growth and soils, to identify any harmful substances, and to study possible methods of reclamation of mud-treated soils.

Objectives

The objectives of this study (which is a portion of a larger overall project) were:

1. To evaluate common drilling mud mixtures for their impact on plant growth.

2. To determine if a simple amendment can be used for reclamation of soils affected by the sodium content of drilling mud.

3. To study reclamation techniques and their effects on soil and on crop responses as tested by beans and corn.

Figure 1. A typical oil well drilling rig and waste pond. Drilling fluids (muds) are needed to cool the bit, seal porous geologic strata, and float rock cuttings out of the bore hole. The mud tanks, left of the rig, appear in the photo as the long flat tanks. Barite for making new mud is in the tall blue hopper at the left edge of the rig. Sacked mud ingredients (bentonite, sodium hydroxide, lignite, and others) are housed in the shed (white) just between the barite hopper and the mud tanks.

The drilling mud waste is mixed with rock powder from the drilling. If the mud is disposed of in the pond, the liquified slurry of the pond is not just drilling muds but consists dominantly of detergents, wash waters, oils, lubricating grease, pipe dope, and other wastes. These studies on drilling muds are only a part of the total information needed. The rig shown is near Vernal, Utah (eight miles north of Duchesne).

REVIEW OF LITERATURE

All drilling muds consist of some or all of the following fractions:

1. A liquid (usually water; but oils and other organics are also used).

2. Non-colloidal solids (starch and lignite, as examples).

3. Colloidal solids (bentonite clay is mostly used).

4. Dissolved chemicals (sodium hydroxide, potassium chloride, and sodium dichromate, as examples).

The fraction in the largest volume is liquid (water or oil or both) although frequently the major component by weight is the suspended, non-colloidal solids such as sand, drill cuttings, and the added density-increasing materials, commonly barite.

Simpson (1975) has classified some types of drilling fluids that are used in the majority of drilling operations today into four categories:

1. Air or gas (mist, foam)

2. Clear water or brine

3. Water muds (clay-base, polymers)

4. Oil-contaminated muds

Each system is used for specific conditions. The condition where air or gas drilling are suitable is: Low formation pressures, strong, competent formations; no highly permeable formations containing water or oil, and shallow depths.

The conditions for which clean-water drilling are suitable are normal or subnormal formation pressures, having no highly permeable formations, and having no extremely water-sensitive shale formations.

In highly permeable formations, there would be loss of the drilling water into the formation, and it would not be possible to maintain circulation. Water sensitive shale would give an unstable hole when drilled with a clear-water system.

If any of these conditions exist, where air or water is unsatisfactory, it is necessary to use a liquid mud. The type of material needed is one that has a high specific gravity. Also, it is necessary to have a material that is (1) as chemically inert as possible, (2) as insoluble as it can be, (3) not too hard, and (4) not too soft. Barite and some polymers (starch-polyacrylamide) are used. The drilling conditions favorable for or requiring oil muds are: Extremely water-sensitive shale formations, deep salt formations, abnormally high pressured formations containing H_2S, formations causing drill bit temperatures exceeding 204 ^oC, and productive formations subject to damage by water.

The mud mixtures are most often used in oil well drilling, partly because of the depth of drilling. Each mud is composed of many components. A recent count of the brand name additives on the market for use in preparing drilling muds exceeded 600, according to Shaw (1975). These components can be categorized into those for (1) cooling and lubricating the drills, (2) flotation of rock pieces, (3) sealing porous layers of the geologic strata, and (4) solving various other problems.

Cooling and lubrication components

The weight of the shaft and the load on the drilling bit is 10,000 to 15,000 pounds per square inch. With this weight the friction of drilling generates considerable heat, 246 ^oC at the total depth of 31,441 feet. The highest temperature recorded in a well was 310 ^oC at about 23,837 feet deep, as examples, even while fluid flowed through the drill head (Loy, 1975).

Common cooling and lubricating components are the fluid itself, sodium saturated bentonite clays, and, for high temperatures, diesel oil. Other materials include organic polymers, carboxymethylcellulose, or polyacrylates.

Flotation components

A heavier (denser) fluid is more capable than water of floating out the dense rock grindings (rock is 2.2 to 4 times as dense as water). The usual material used to increase density is barite ($BaSO_4$) which has a density of about 4. A thin suspension of dispersed bentonite aids in keeping the barite suspended. Two other weighting materials that are used, although less frequently than barite, are calcite ($CaCO_3$) and siderite (iron carbonate) (Grantham and Sloan, 1975).

Components that seal porous formations

As drilling passes through some geologic strata such as sandstones or shales, drilling fluid may be lost in excessive amounts unless the porous area is sealed. Various materials and mixtures, usually including chemicals for the flocculation of the clays and the inclusion of fibers of some type are used. Some of these materials are (Collins, 1975): calcium chloride, calcium sulfate, calcium oxide, calcium lignosulfonate, sodium chloride, sodium silicate, colloidal asphalt, sulfonated asphalt, polyanionic cellulose, gilsonite, and aluminum lignosulfonates.

Various materials are added to obtain the fluidity properties, to increase the stability, and, generally, to improve the rheology (the nature of the deformation and flow of gelatinous matter), the thixotropy (the property possessed by certain gels of repeatedly becoming fluid on agitation and again gelling when at rest (Baroid, 1954)), and other properties. Some of these common substances are given in Table 1.

Table 1. Materials used in well drilling muds to alter the physical properties of the fluid, particularly its rheologic and thixotropic properties (Collins, 1975)

Substance	Purpose
Sodium carboxymethylcellulose	Viscosifiers
Bentonite clay	Reduce filter loss, increase viscosity and gel strength, and as a coagulation agent
Barium carbonate	Precipitation agents
Oil-base mud	Reduce friction coefficient, help control fluid loss, and for lubrication
Various lignosulfonates	For clay dispersion or thinner
Sulfonated asphalt (Soltex^{R})	Emulsified oil-shale stabilizer, and reduces fluid loss
Pregelatinized starch	Reduces fluid loss

Categorizing Drilling Fluid Components

In the previous section, drilling fluid components were categorized according to their purpose in the mud. However, they can also be grouped on the basis of their chemistry or other properties when evaluating the properties of the materials added to soils. Some of the likely groupings are as (1) petroleum products, (2) organics of plant origin, (3) inert or soluble inorganics, (4) soluble salts, and (5) miscellaneous.

Materials containing petroleum products

Common materials of petroleum origin are crude oil, diesel oil, asphalt, pipe dope (not in drilling muds, but used on the rig) and modified asphalt (Soltex^R). Of these, crude oil (as a contaminant in the waste) and diesel oil because of its known phytotoxicity, are of greatest concern (Honarvar, 1975).

Crude oil. Oils contain at least four types of hydrocarbon molecules: parafins, naphthenes (saturated carbon rings), olefins, and aromatics (Van Onerbeek, and Blandeau, 1954). In general, the smaller the hydrocarbon molecule, the more toxic the oil is to plants (van Overbeek and Blondeau, 1954; Johnson and Hoskins, 1952). Molecule size affects boiling range and viscosity. Havis (1950) found that the boiling range was related to toxicity independently of the hydrocarbon series. High-boiling materials may have molecules too large to penetrate plant tissues and volatile oils may evaporate from the soil before they have any effect on the plant.

Oil is absorbed by the roots and moves upward. Most workers believe that the oil moves primarily in the intercellular spaces, with little or no movement through the vascular system. Yet, some researchers claim that there is some translocation in the vascular system (Baker, 1970).

Oils vary in their toxicity according to the content of low boiling compounds, unsaturated compounds, aromatics, and acids. The higher the concentration of these constituents, the more toxic the oil.

Oil reduces transpiration rate and photosynthesis. The effects of oils on respiration are variable but an increase of respiration rate often occurs, possibly due to mitochondrial damage resulting in an "uncoupling" effect (Green, 1936; Wedding et al., 1952).

Cowell (1969) found that weathered crude oil is less toxic to salt marsh vegetation than fresh oil, probably because the fresh oil contains more of the low boiling compounds. Other researchers have also discussed toxicities to plants of various oils (Carr, 1919, Deong et al., 1927; Tucker, 1936; Denison, 1944; Crafts and Reiber, 1948; and Coats and Foy, 1974).

Diesel oil. Diesel oil is one of the materials of petroleum origin used in this study. It may be a refined high boiling kerosene or a refined low-boiling gas oil. In general, hydrocarbons within the boiling range of 150-275 °C (naphtha and kerosene fractions) are most toxic to plants (Baker, 1970).

The most phytotoxic of the materials in diesel oil are volatile and should disappear within a few months or at most a few years. Heavier portions of the fuel might adsorb to the soil and make the soil temporarily or partially water-repellent.

Other materials of plant origin

Other commonly used materials which are of plant origin include lignite (coal-like organic), lignosulfonates, pregelatinized and other starches, paraformaldehyde, and polyacrylamide (Separan AP-273[R]).

Lignite. Lignite, as an organic additive to drilling muds, is a very useful and versatile material. It is a free-flowing powder used as a mud thinner (Baroid, 1954). Lignite is not toxic to plants and may have some benefits as a source of energy to microbes; it affects the mineralization of organic matter.

Lignin. Lignin, a plant constituent, is found in the cell wall of plant materials in close proximity or association with cellulose. It is insoluble in hot water and neutral organic solvents but is solubilized by alkali.

The cause of any plant growth retardation by lignin is unclear, although the effect is thought not to be physiological, at least not in the sense of a toxicity. Its effect in retarding the microbiological degradation of organic constituents of crop materials probably results from a physical or physio-chemical barrier set up by the close inter-linkage between lignins and the hemicelluloses and cellulose of the plant cell wall (Alexander, 1961).

Lignosulfonates. The lignosulfonates are man-modified lignin materials (distinguished from altered organic residues of lignites) and are mostly processed wastes from wood (Baroid, 1954; Hollingsworth and Lockhart, 1975).

The lignosulfonates have the particular ability to disperse colloid clays in the presence of calcium. Lignosulfonates contain as part of their structures linked phenolpropane molecules; the free phenolpropanes have been found to be toxic to plants (Wang et al., 1967; Patrick, 1971). These phytotoxic compounds are released during decomposition of plant residues under anaerobic conditions.

Starches. Pregelatinized starch is an amylose carbohydrate (sugar units) with 7.5 percent protein. It should not retard plant growth unless its presence (or that of other starches) caused unfavorable alteration of the physical soil environment, such as poor aeration. This and other starches could even be sources of energy to beneficial microbes (Honarvar, 1975).

Paraformaldehyde. Paraformaldehyde, a polymer of formaldehyde, is used in low amounts to hinder microbial growth in the muds during mud use (Robichaux, 1975). It does not appear to be a problem to plant growth at normal use rates (Honarvar, 1975).

Polyacrylonitriles. Separan AP-273, the polyacrylonitrile used in this study, is a flocculant for maintaining a low-solids content. It is similar to hydrolized polyacrylonitriles (HPAN), which is a soil conditioner. HPAN has been used to improve the soil's physical condition and has not been found to be toxic to plants (Allison, 1952; Martin and Jones, 1954; Bernstein and Pearson, 1956; Mortenson and Martin, 1956, and Honarvar, 1975).

Inorganics of low solubility

The most important low solubility inorganics used in drilling muds are bentonite (montmorillonite clay) and barite, $BaSO_4$. Both materials are essentially insoluble for all practical purposes in influencing soil properties or plant growth.

Bentonite. Bentonite is an impure deposit of montmorillonite or beidellite clays. These clays possess important and unique properties (enormous adsorptive surface area, dispersability, inertness, and cohesiveness) which give them great commercial value for decolorizing of oils, in the manufacture of catalysts, in bonding molding sands, and in the preparation of oil drilling muds (Grim, 1967).

Bentonite is a constituent of all mud mixtures. In these mixtures sodium is a major exchangeable cation, and sodium is always added to the mud for this purpose (Grim, 1962; Bear, 1964; and Grimshaw, 1971).

Montmorillonite is a clay mineral made up of planes of oxygens (and a few hydroxyls) held together by silica and aluminum, mostly. Its formula can be written as $(Al,Mg)_4\ (Si)_8\ O_{20}\ (OH)_4$. The forces which hold the layers within each montmorillonite particle together are relatively weak and water molecules tend to move into and out of the interlayer areas with relative ease. This movement of water in between and out of the interlayer space gives montmorillonite its characteristic swelling and shrinking properties (Grim, 1962, 1967; and Jurinak, 1975b).

Bentonite helps to prevent the cuttings from settling back around the drilling pipe and bit. The thixotropic property of the bentonite is helpful. Thixotropic means that the mud suspension is a gel-forming colloid material which temporarily sets up like gelatin when undisturbed but will flow readily when stirred (agitated) or mixed.

Thixotropy is also discussed in terms of "sensitivity" as defined by Terzaghi (1944). According to his definition, "sensitivity is the ratio of the strength of the soil in an undisturbed state to the strength of the remolded material at the same moisture content." Strength in this use would be strength to support rock particles so they won't settle out.

Insensitive clays have sensitivity of less than one, sensitive clays have values between four and eight, and "quick clays" have values more than sixteen (Grim, 1962). A high sensitivity is desirable. When some remolded clays with moderate to high sensitivity are allowed to stand without the loss of moisture, they show a regain in strength. From previous studies, bentonite does not have toxic effects on plant growth (Honarvar, 1975), but its properties such as swelling, gel-forming, plasticity, and thixotropy can cause possible side effects which will be discussed later.

Barite ($BaSO_4$). Barite does not contain any known toxic elements. Tests by Honarvar (1975) did not exhibit any reduced plant growth due to barite; in fact, the greatest nodulation of *Rhyzobium* nitrogen fixers occurred on beans grown in about 40 percent by volume of barite-in-soil mixture. Its solubility is very low; a classical quantitative chemical method to determine sulfate content is to weigh precipitated barium sulfate.

Materials with soluble salts

The common chemicals of moderate to high solubility which are added to drilling muds include (1) sodium hydroxide, (2) sodium dichromate, (3) potassium chloride, (4) potassium hydroxide, and (5) calcium hydroxide. Some of the quantities used and solubilities of these materials as given in the Handbook of Chemistry and Physics (1974) are:

Materials	Solubility in water g/100 ml at °C
Sodium hydroxide	42.0 (0 °C)
Sodium dichromate	238.0 (0 °C)
Potassium chloride	27.6 (0 °C)
Potassium hydroxide	107.0 (15 °C)
Calcium hydroxide	0.185 (0 °C)

Miscellaneous materials

Many additional mud components have additional effects on plant growth when they are added to soils. The action of chromium itself, formaldehydes, and amine are some of these materials.

Toxicities to the plant or to an animal eating the plant can both be problems. The use of dichromate could be such a problem. Chromium is more toxic to animals than to plants. Chromium (Cr) is considered an indispensable microelement for certain plants. Although the plant content normally is low (0.01-0.1 ppm), some species can accumulate an appreciable quantity (Myttenaerna and Mousny, 1974). The concentration of Cr in soils has been given in the range of "a trace" to 250 ppm, as Cr_2O_3 (Mertz, 1969). Values as high as 7,600 ppm in soils were found by Lyon et al. (1970).

Chromium increased the growth and development of seedlings and grafts of grape vines and improved the yield and sugar content of grapes in Russia (Dobrolyubskii, 1958). When chromic-sulfate was applied either to the soil (600 g/ha) or directly to the vine (200 mg/bush), the weight of grapes improved by 21 percent, the size and sugar content by 18 percent and 23 percent, respectively, and yield increased from 205 in untreated to 245 kg/ha for the treated plots (Mertz, 1969).

Huffman and Allaway (1953) found no significant response in romaine lettuce, tomato, wheat, and bean growth when Cr was added (3.8×10^{-4} μm) in solution culture. Yet, there is much evidence that chromium is toxic to plants (Hunter and Vergnano, 1953; Soane and Saunder, 1959; Mertz, 1969; Breeze, 1973; Gemmel, 1974; Committee on Biologic Effects of Atmospheric Pollutants, 1974; and U.S. National Committee for Geochemistry, 1974).

Chromium is also an important constituent of drilling muds. In chromolignosulfonates and very likely in the presence of any appreciable amount of organic matter, chromium is present in its trivalent form, and bound quite strongly to organic matter, as occurs in the iron chromolignosulfonate, Q-Broxin^R. The binding of chromium by organic matter may make chromium unavailable to aquatic fauna and flora and significantly reduce its toxicity. In the absence of organic matter, chromium is highly toxic, at least to certain species. The reported concentrations causing toxicity are 0.01-76 and 0.05-133 mg/l for tri- and hexa-valent chromium in the plant, respectively (Zitko, 1975).

Other materials may be added such as bactericides to drilling muds and complexing fluids to prevent microbial degradation of organic additives, and to suppress the formation of corrosive gas, H_2S, by sulfate reducing bacteria. The chemical types of bactericides or pipe coatings used are aldehydes (formaldehyde, paraformaldehyde), chlorinated phenols, quaternary amines, and alkyl amines. Bactericides will be carried into the aquatic environment readily, thus posing a hazard to fish and birds as well as to the water supplies of man (Robichaux, 1975).

Fiber mixtures to plug porous geologic strata include a variety of mixtures from the simple mineral asbestos to mixtures of many materials such as Kwik-Seal^R. The compositions of most mixtures are trade secrets and thus their evaluation is difficult.

Complete Drilling Fluids

Drilling fluids are made as simple as possible to get the job done well. Although many mixtures can be made, most muds have several basic ingredients. A typical mud base would be approximately

Water	300 milliliters
Bentonite	20 grams
Barite	200 grams
Sodium hydroxide	2-20 grams
Organic dispersant	4-10 grams
(lignite or related material)	

In such a mud, the bentonite with the aid of the organic dispersant suspends the density-building barite. The sodium hydroxide insures adequate dispersion by furnishing sodium as an exchangeable ion and by keeping the pH alkaline (often near pH 9) at which pH the organic dispersant works best. The organic dispersant bonds to clay edges. When high-pH lime muds are used, larger amounts of sodium hydroxide are used, enough to keep the pH near 12. Such muds would be problem growth media without considerable dilution with acid soils.

Other components, such as diesel oil, are also commonly added, again causing a new type of problem, that of water repellancy and phytotoxic hydrocarbons.

Anticipating the Effects of Drilling Fluids

An evaluation of the potential effects of drilling fluids on soils and plants involves at least these possibilities: salt concentrations that are too high, excessive amounts of sodium which would form sodic soils, and several other less obvious problems such as organic phytotoxins or heavy metal (chromium) toxicities.

Effects of salts

Excess salts, although a problem that can be corrected, will inhibit plant growth. The detrimental effects of salt in the soil solution on plant growth are attributed to:

1. Development of osmotic pressure in the soil solution making water uptake by plants more difficult.

2. Interference because of large concentrations of certain ions, with normal nutritional balance and metabolism of plants.

3. Toxicity to certain plants of specific ions, such as sodium, occurring in large concentrations (Wadleigh and Ayers, 1945; Kovda, 1947; Wadleigh et al., 1951; Bernstein, 1964; Richards, 1969; Taylor and Ashcroft, 1972; and Jurinak, 1975b).

The presence of salt increases the soil solution's osmotic pressure, which, in turn, increases the energy the plant must expend to extract water from the soil. Soluble salts increase the osmotic pressure of the tissue fluids in both roots and tops of plants, decreases the rate of vegetative growth, modifies the opening of the stomata, causes a depletion of starch reserves, causes a decrease in apparent photosynthesis, and causes an increase in respiration (Wadleigh and Ayers, 1945; Kovda, 1971). Also, salt causes a delay in germination, flowering, and ripening (Kovda, 1971; Bernstein, 1964; and Richards, 1969).

The exact extent to which increased concentration of salts in soil solution decreases plant growth has been studied by various workers. The following categories have been widely accepted (Jurinak, 1975).

Table 2. Crop response to salinity

Mmhos/cm at 25 °C	Osmotic pressure atms	Crop response
0- 2	0 -0.72	All crops grow
0- 4	0.72-1.44	Salt sensitive
4- 8	1.44-2.88	Many crops have yields reduced
4-16	2.88-5.76	Only salt tolerant crops produce adequate yields
>16	>5.76	Few crops will grow

Such a generalization is not likely to be accurate for all plants. A soil solution having a conductivity as low as 2 mmhos/cm may contain enough salt to reduce growth in sensitive plants. The following general guides for the reduction of growth of sweet corn and garden beans (Bernstein, 1964):

Reduction in growth	Solution conductivity mmhos/cm	
	Beans	Corn
10 percent	1.5	2.5
25 percent	2.0	4.0
50 percent	3.0	6.0
No growth	5.0+	8.0+

Effects of sodium on soil dispersion

A soil is considered to have a potential "sodium hazard" when the sodium adsorption ratio (SAR) of the saturation extract is >13, that is ESP > 15, and pH > 8.4 (Richards, 1969). If the concentration of salt is not high, these soils are called sodic soils. The predominant problems of sodic soils are the reduced aeration because of excessive swelling of clay when wet, toxicities from the sodium, the marked crusting of the dried soil, and the lowered infiltration rates (Ulrich and Khan, 1972). Problems of poor aeration are caused by an increasing zeta potential near the clay mineral surface when appreciable exchangeable sodium is adsorbed. When the sodium in the double layer near the particle surface causes the expansion of the ionic layer to a layer thicker than 40 A^{o}, the aggregates disperse. The resulting swollen soil has reduced permeability to both air and water.

Sodium toxicity. Sodium is toxic to certain plants. In addition, large concentrations of exchangeable sodium ions raise the pH in the soil above optimum growth levels. It has also shown that the hydroxyl concentrations at high pH are toxic to plant growth, over and above its influence on pH (Allison, 1964; and Jurinak, 1975b).

Infiltration in changes and crusting. In sodic soils the hydraulic conductivity can decrease to the extent that no water movement occurs (Taylor and Ashcroft, 1972). A clay platelet with a high proportion of adsorbed Na^{+} develops a thick, diffuse double layer which, as was just mentioned, produces colloidal peptization of the clay (Tersaghi and Peck, 1948; Grim, 1962; Bear, 1964; Grimshaw, 1971; and Jurinak, 1975a). The dispersed soil moves into pores plugging the channels through which water may flow. The soil is very plastic when wet and becomes very hard when dry. Hard soil crusts occur (Jurinak, 1975b). Soil crusting apparently is influenced by two factors, namely: (1) external factors which supply the energy, and (2) the inherent characteristics of the soil. Various studies have shown that soil crusting results from a combination of compaction, structure breakdown and deposition of fine particles at the surface (Lemos and Lutz, 1957). Evans and Buol (1968), who studied crusting in detail, listed swelling of the soil matrix as an important causative factor.

Part of the concern about surface crusts is that they reduce water intake and evaporative loss, thereby increasing runoff and erosion. Crusts may also interfere with the necessary interchange of O_2 and CO_2 between the soil and atmosphere. They can also hinder or inhibit seedling emergence if they are thick enough and hard enough (Evans and Buol, 1968).

Falayi and Bouma (1975) studied the management of soil crusting by using two practical factors, namely tillage practice and crop rotations. Timing tillage and keeping organic matter and aggregation high reduces crusting.

Other problems

Other possible problems from drilling fluids are many but variable. These include possible changes in soil wettability as oils are added. Diesel oil, a prominent ingredient of deep well drilling muds, has volatile components, but will also have a variable residual period during which it will coat soil particles making them water repellent.

Other possible problems are so numerous, and often of unknown causes, that they will be tabulated here and discussed in the results and discussion later where they are appropriate.

1. Possible toxic levels of chromium

2. Phyototoxic decomposition products of lignosulfonates or other organic materials.

3. Sponge-like action of starches and fibers in holding excess water in soil causing aeration problems or production of anaerobic phytotoxic products.

Reclamation of Saline, Sodic, and Saline-sodic Soils

The greatest anticipated problems of the drilling fluids studied are of excess salt and excess exchangeable sodium. These fluids should form saline and/or sodic soils. Their reclamation will be needed.

Reclamation is the correction of a soil problem. In the case of saline, sodic, or saline-sodic soils, reclamation is altering the soil so it can be used for the growth of plants. Solving the problems of sodic and saline sodic soils include the removal of excess salts, the elimination of detrimental amounts of exchangeable sodium, the improvement of the physical condition of the soil, and the elimination of any toxicities that occur. Adequate knowledge to accomplish these objectives to a moderate degree of satisfaction is available but there is much yet to be learned to improve the techniques.

Reclaiming saline soils

Saline soils are reclaimed by removing most of their salt load by leaching. The amount of water needed to remove excess salts is related to the water required in excess of that to wet the soil profile. This excess water is called the leaching fraction. The leaching requirement, which is the water to wet the soil plus the leaching fraction, is different for each water because of the salt content of the water.

The maximum allowable slainities of soil solution and irrigation water also depend on crop tolerance.

There are many methods of adding water to leach salts from soils, for example, sprinkling, intermittent ponding, continuous ponding, and trickle irrigation. Sprinkling is the most efficient method of salt removal per unit volume of water. Intermittent ponding is the second most successful method, and due to the large quantities of water involved, often moves the salt to deep depths. Continuous ponding, due to water logging and associated problems, is only moderately successful and is expensive per unit volume of salt removed (Bandyopodhya, 1973).

Recent laboratory work (Nielson and Bigger, 1961; Keller and Alfaro, 1966) and some carefully controlled field experiments indicate that the efficiency of salt leaching was greatly increased by controlling the soil water content and flow velocity of water during leaching. Unsaturated flow was more efficient in water use than when saturated flow dominated flow of water through the soil most of the time.

Reclamation of sodic and saline-sodic soils

In principle the reclamation of a sodic soil is not difficult. It requires these three actions:

1. Replace exchangeable Na^{+} by Ca^{++} or other nondispersing ion (Bear, 1964; Richards, 1969; and Jurinak, 1975b).

2. Increase permeability (Sahota and Bhumblu, 1970; Randas, 1970; O'Conner, 1972; and Jurinak, 1975b).

3. Leach sodium salts from the soil. Although the concepts of sodium replacement and leaching of salts is simple, the actual

replacement of exchangeable sodium and leaching of salts from the profile in the field is seldom easy. The soil frequently has a low water permeability. This makes it difficult to accomplish the removal of exchanged sodium and of salts by leaching. The soil's physical problems caused by the dispersed condition are slow to improve.

When a sodic soil is leached with a water of low-salt content, the permeability may rapidly decrease to a value that practically prevents completion of the reclamation process, but, by increasing the electrolyte concentration of the water, the transmission rate can be maintained or materially increased. The effects were demonstrated by Fireman and Bodman (1940), Christiansen (1947), Reeve and Bower (1960), Chaudhry and Warkentin (1968), and others.

The high salt-water dilution method of reclaiming sodic soils makes use of the flocculating effect of high-electrolyte waters to maintain a substantially higher permeability. At the same time, the high-salt water serves as a source of divalent cations for replacing sodium (Reeve and Bower, 1960; Reeve and Doering, 1966).

Gypsum is frequently used an an amendment, but because of its low solubility in water, in many instances it is not effective in maintaining a high permeability. Highly soluble calcium salts such as $CaCl_2$ or $Ca(NO_3)_2$ may be used to supply calcium at a high electrolyte concentration, but for the most part, the high cost of these salts makes this impractical (Reeve and Bower, 1960).

For replacing exchangeable sodium, three classes of amendments can be used (Jurinak, 1975b).

1. Soluble calcium salts ($CaCl_2$, $CaSO_4 \cdot 2H_2O$).

2. Acids or acid formers (sulfur, sulfuric acid, iron sulfate, and lime sulfur).

3. Calcium salts of low solubility (ground limestone and by-product lime from sugar factories).

The selection of a suitable amendment depends on soil pH, amount of lime in the soil and some other factors. Also in using each amendment a certain procedure should be followed. Here are some examples of different procedures.

In a laboratory experiment columns of a clay soil had a pH of 9.6, electrical conductivity of 13 mmhos/cm, and an ESP of 19.8 percent. When $CaSO_4$ was added at only one tenth of the full rate, it reduced the exchangeable sodium percentage (ESP) to about 10 percent in the top 2-4 inches of soil which increased the apparent infiltration rate from .09 to .48 cm/hr (O'Conner, 1972).

In another example, gypsum, sulfuric acid, and sulfur were applied in equivalent amounts (10, 5.7, and 1.86 tons/acre, respectively) to a severely affected sodic soil, the Fresno series. For two years after application of the treatments, the yield of plants on sulfuric acid-treated soils were higher than those of the plants on soils treated with gypsum or sulfur (Overstreet et al., 1951)

In a third example, the applications of gypsum, sulfur, iron sulfate and aluminum have produced important chemical changes in the black-alkali soil near Fresno, California. It was found that gypsum had precipitated the soluble carbonate as calcium carbonate, while the other materials have either decomposed carbonate or else converted it into bicarbonate (Kelley and Arany, 1928).

Previous Studies Using Drilling Fluid Components

Honarvar (1975) tested 31 drilling fluid (mud) components on plant growth and concluded the following:

1. Drilling mud components (mixed at normal rates in soil) that caused no reductions of plant yield growing on an excellent soil were the following: asbestos (Super Visbestos^R), asphalt, a vinyl acetate and maleic anhydride copolymer (Ben-Ex^R), bentonite, sodium polyacrylate (Cypan^R), a ethoxylated nonyl phenol (DME^R), a gilsonite (Super Lube Flow^R), paraformaldehyde, a Dow-made, Shell-supplied polymer (Separan-AP-273^R), sodium acid pyrophosphate, and sodium carboxymehtyl cellulose.

2. Drilling mud components on which plant growth reduction on only one of two species was barely statistically significant (at the 5 percent level) are of questionable hazard to plant growth. These materials were Barite ($BaSO_4$), a modified tannin (Desco^R), a filming amine (Drillaid 405^R), a Xanthan gum (Kelzan-XC^R), pipe dope, a lignite (Ligco^R), a modified asphalt (Soltex^R), and a sulfonated tall oil (Witconnate 1840^R).

3. Drilling mud components causing significant reduction in plant growth mostly at only the high excess addition rates of soil-mud mixtures are: a modified tannin (Desco^R), a non-fermenting starch (Dextrid^R), pregelatinized starch, an iron chromelignosulfonate (Q-Broxin^R), a guar gum (Gendril Thik^R), and a synthetic and plant fiber mixture (Kwik-Seal^R).

4. The most severe reductions in plant growth were caused by the following materials: Sodium hydroxide at the high rate (which was used in the soil-mud mixture with calcium lignosulfonate and with lignite), sodium dichromate, diesel oil, and potassium chloride.

MATERIALS AND EXPERIMENTAL PROCEDURES

Drilling Fluids

The drilling fluids were prepared under the direction of Darryl Giddens, a professional drilling fluid analyst, through the courtesy of Jay Simpson and Baroid Division of the National Lead Company in Houston, Texas.

In Table 3, the compositions are given for the seven muds used. The few modifications from predetermined compositions which were made during mixing are indicated by a notation under each mud. These modifications were considered to be necessary for correct properties and were made by Mr. Giddens during the mixing.

Each fluid component used in making the muds is described in the following pages from information available in the literature and from the suppliers of the materials. Properties of individual components will often change after mixing with other materials making up the mud mixture. In Table 4, the pH values of the prepared mud mixtures are given.

Details of Individual Components of Mud

1. Barite ($BaSO_4$). In drilling fluids barite accounts for 98 percent of all weighting agents used. It is inert (insoluble) in moderately alkaline, acidic, and neutral solutions; it is low in cost; it has a high density (about 4); and it is commercially available worldwide (Grantham and Sloan, 1975).

Table 3. Preplanned compositions of the seven drilling fluid mixes used and the slight modifications made during mixing as judged to be needed by Darryl Giddens, drilling fluid specialist. Changes are indicated by notes to each fluid

Mud number, composition, and code symbol	Weights used in each mixture†
	grams
Mud 1. Potassium chloride mud (PCM)	
Water	294
Bentonite	10
Potassium chloride	17.5
Sodium hydroxide	0.2
Pregelatinized starch	6.0
Polyacrylamide (Separan AP-273)	0.5
Paraformaldehyde	0.3
Barite	194
Mud 2. Dichromate-treated mud (DTM)	
Water	294
Bentonite	20
Lignite	10
Sodium hydroxide‡	0.5
Sodium dichromate	0.5
Barite	194

‡Sodium hydroxide was inadequate and the quantity was increased 45 percent for a total of 0.727 g rather than 0.5 g per unit volume given above.

Mud 3. High-pH lime mud (HPLM)	
Water§	294
Bentonite	20
Calcium lignosulfonate	4
Sodium hydroxide	2
Calcium hydroxide	3
Pregelatinized starch	6
Barite	194

§Water was increased by 2500 ml in the batches, an increase of 4.8 percent in the water volume used which reduces other component concentrations by about 4.5 percent.

Table 3. Continued

Mud number, composition, and code symbol	Weights used in each mixture†
	grams
Mud 4. Lignite-lignosulfonate sodium mud (LLSM)	
Water	294
Bentonite	20
Lignite	4
Iron chromolignosulfonate (Q-Broxin)	6
Sodium hydroxide	1
Barite	194
Mud 5. Lignite-lignosulfonate potassium mud (LLPM)	
Identical to Mud 4 except for substitution of potassium hydroxide in place of sodium hydroxide:	
Potassium hydroxide¶	1.0

¶Since potassium hydroxide is heavier than sodium hydroxide, to add equal molar amounts the actual amounts added were 1.4 g

Mud 6. Diesel oil emulsion mud (DOEM)	
Water	294
Bentonite	20
Lignite	4
Iron chromolignosulfonate (Q-Broxin)	6
Sodium hydroxide	1
Diesel oil, No. 2	5
Barite	194
Mud 7. Mud base (MB)	
Water	294
Bentonite	13
Barite	194
Sodium hydroxide	1

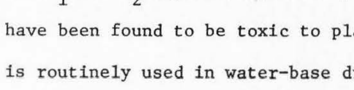
†The values given in grams are equal to pounds of material needed per barrel (42 gallons) of mud preparation.

Table 4. Final pH of the mud mixtures after preparation and before addition to the soil.

Drilling fluid (Mud)	pH
Diesel oil emulsion mud (DOEM)	8.5
Dichromate-treated mud (DTM)	9.9
High-pH lime mud (HPLM)	12.6
Lignite-lignosulfonate potassium mud (LLPM)	9.5
Lignite-lignosulfonate sodium mud (PPSM)	10.4
Mud base	9.7
Potassium chloride mud (PCM)	11.2

2. Calcium hydroxide [$Ca(OH)_2$]. Calcium hydroxide is a soluble base and is less alkaline than sodium hydroxide; a saturated solution has a pH of about 12 (Baroid, 1954).

3. Calcium lignosulfonate. This material, produced from lignin materials is extracted in the manufacture of paper. It helps to disperse the clays (Baroid, 1954). Calcium lignosulfonate is a substituted phenolpropane:



The R_1 and R_2 may be additional phenolpropane molecules, some of which have been found to be toxic to plants (Patrick, 1971). This material is routinely used in water-base drilling muds at concentrations varying from 2 to 10 g/350 cc (2 to 10 lbs/bbl) and at temperatures approaching $400^{o}F$ (Hollingsworth and Lockhart, 1975).

4. Diesel oil. Common diesel oil is an intermediate-molecular-weight petroleum distillate. No. 2 diesel oil was used in this study.

5. Lignite (Ligco[R]). Drilling-mud-grade lignite is a polymeric humic acid with a complex and extremely variable organic structure containing about 10 percent inert inorganic solids. Lignite and its various derivatives are normally used in concentrations from 2 to 12 g/350 cc (2 to 12 lbs/bbl) of drilling mud (Hollingsworth and Lockhart, 1975). It is used to emulsify oils in water-based drilling fluids and to control filtration rates of these fluids (Miller and Honarvar, 1975).

6. Paraformaldehyde. This preservative is used to hinder microbial oxidation of starch. It is a polymer represented by $(CH_2O)_x$ (Miller and Honarvar, 1975).

7. Potassium chloride (KCl). This soluble salt is used in combination with other chemicals, such as Separan AP-273. The high salt content helps stabilize sensitive shales (clayey) formations encountered while drilling. Any soluble salt is known to severely reduce plant growth at levels of a few tenths percent in soil (Honarvar, 1975).

8. Potassium hydroxide. This strong base is similar to sodium hydroxide but does not result in high sodium percentages in the mud nor does it cause the extent of soil dispersion caused by sodium.

9. Pregelatinized starch. This starch, one of several used, is an amylose carbohydrate (chain of amylose sugar units) with 7.5 percent protein. It is used as an agent to reduce fluid loss into geologic strata (Honarvar, 1975).

10. Iron chromelignosulfonate (Q-Broxin[R]). This modified lignosulfonate is used primarily as a thinner or dispersant to lower the apparent viscosity and gel strength of mud. Sodium hydroxide

(caustic soda) is usually also used with it to form a mud of pH 9 to 10 (Miller and Honarvar, 1975). Q-Broxin is prepared by a dichromate oxidation of the sulfite-pulp-lignosulfonate liquor obtained from paper manufacturing (Hollingsworth and Lockhart, 1975). Use rates are 1 to 20 g/350 cc (1 to 20 lb/bbl) with a typical rate of 6 g/350 cc (6 lb/bbl).

11. Hydrolyzed polyacrylamide (Separan AP-273[R]). This material at low concentrations of 25-50 ppm (about 0.008-0.018 lb/bbl), is a flocculant for maintaining a low-solids content. At rates of 1000 or 3000 ppm (0.3 to 1.0 lb/bbl), in combination with 3 to 15 percent KCl, Separan stabilizes water-sensitive shale formation encountered while drilling. It has a molecular weight of 3×10^6 or greater and a formula as follows:

$$\left[- \begin{pmatrix} CH - CH_2 \\ | \\ COOH \end{pmatrix}_{0.3} - \begin{pmatrix} CH - CH_2 \\ | \\ CONH_2 \end{pmatrix}_{0.7} \right]_n$$

Separan AP-273 is a partially hydrolyzed polyacrylamide and is similar to hydrolized polyacrylonitrile (HPAN), differing mostly in extent of hydrolization. HPAN is a soil conditioner which has been used to form stable soil structure (Miller and Honarvar, 1975).

12. Sodium dichromate. This soluble chromium salt is presumed to be for making the salt of lignosulfonates, which more strongly bonds the organic molecule through the chromium or the oxidized group to clays. It aids the action of the lignosulfonate or lignite. Its chemical composition is $Na_2Cr_2O_7$ (Miller and Honarvar, 1975).

13. Sodium hydroxide (NaOH), called caustic soda, is a strong alkali. A solution of 25 g of NaOH/350 cc of water (25 lb/bbl) has a

pH of about 13.8. Sodium hydroxide, when used to maintain the pH above 11.5, serves to prevent the growth of micro-organisms that would cause starch degradation (Baroid, 1954). Sodium hydroxide is a well-known soil dispersant, and it is often used in drilling muds with calcium lignosulfonate, lignite, and Q-Broxin, resulting in muds having a pH of 9 to 10 (Miller and Honarvar, 1975).

Treatments Used

This study involves six soils, two soil:mud ratios, seven mud mixtures, and a leaching treatment. Table 5 presents the characteristics of the six soils used: Dagor and Millville series from Cache Valley, Utah; an unnamed North Carolina soil; a Kidman series from Farmington, Utah; and A_2-horizon material from an unnamed soil under lodgepole pine labelled MU-2-74; and Miamian series from Ohio.

The mud mixtures were prepared prior to adding the muds to the air-dry soil. Two ratios of mud to soil were used: (1) equal volumes of both liquid mud and soil, a 1:1 ratio (1200 cc of mud and 1200 ml of soil); and (2) one volume of liquid mud to four volumes of soil, a 1:4 ratio (350 cc of mud and 1400 cc of soil)(see Figures 2 and 3). To avoid puddling the soil during the initial mixing, the mud and the soil were mixed very slightly and cautiously. When the slightly mixed soil-mud mixtures were air dry, they were crushed to pass a quarter-inch screen.

Table 5. Characterization data for soils used. Dagor soil was used for the first year's studies

Soil*	Textural class	Organic matter	Soil pH paste	Cation exchange capacity	Moisture at 1/3 bar	Exchange-able potassium
		%		me/100 g	%	kg/ha-15 cm
Dagor	Silt loam	8.1	6.2	42.4	36.5	1150
Kidman	Fine sandy loam	1.8	7.4	12.2	17.2	382
Millville	Silt loam	2.1	7.7	11.7	20.9	470
Miamian (Ohio)	Silt loam	3.3	5.8	15.2	32.4	223
MU-74-2	Sandy loam	0.3	6.3	5.8	18.0	154
North Carolina	Clay loam	2.8	5.5	7.4	15.8	80

*Soil classifications based on Soil Taxonomy are as follows:
Dagor: Cumulic Haploxeroll, fine-loamy, mixed,mesic.
Kidman: Typic Haplustoll, coarse-loamy, mixed, mesic.
Millville: Typic Haploxeroll, coarse-silty, carbonatic, mesic.
Miamian: Typic Hapludalfs, fine, mixed, mesic.
MU-74-2: Not surveyed, probably a Typic Cryoboralf, sandy-skeletal, mixed, cryic.
North Carolina: Not identified.

Coding System for Treatments

The coding system used consists of four groupings of symbols, i.e., DA-DOEM-LE-H1. The first group (DA) indicates the soil; the second group (DOEM) identifies the mud used; the third group (LE) refers to the leaching treatments, and the fourth group (H1) is the soil:mud ratio used, the identity of the crop, and the replication number. These coding systems are shown in Table 6 in detail.

Figure 2. The mud was poured onto soil on plastic sheeting and allowed to air-dry. This required about 2 to 5 days.

Figure 3. A few of the 750 plus samples as they appeared after mud was ponded on the soil and air dried prior to mixing.

Table 6. Description of the code symbols used for pot identification in Phase II

1. Soils:	DA = Dagor KI = Kidman MI = Millville	MN = Miamian MU = MU-2-74 NC = North Carolina
2. Muds:	PCM = Potassium chloride mud DTM = Dichromate treated mud HPLM = High pH lime mud LLSM = Lignite-lignosulfonate sodium mud LLPM = Lignite-lignosulfonate potassium mud DOEM = Diesel oil emulsion mud MB = Mud base	
3. Treatment:	LE = Leaching only O = No reclamation treatment	
4. Levels and crop:	L = 1:4 Mud:Soil mixture, by volumes H = 1:1 Mud:Soil mixture, by volumes 1,2 = Bush green beans, Tendergreen (Phaseolus vulgaris) 3,4 = Sweet corn, NK-199 (Zea mays succharata)	
5. Typical code examples:	DA-DTM-LE-H3 NC-DOEM-O-H1	

Reclamation Procedure

Part A

Initially the leached treatments were to have had soluble salts removed by leaching using only tap water. For leaching the soil, it was anticipated that a 6-inch depth of water might be enough to allow growth of plants. Because there was inadequate drainage for leaching using only water, leaching on all treated pots was immediately discontinued and the unleached pots were planted. Later, when it was certain that plants would not grow normally on the unleached soils, a different method of leaching on these pots was done after harvest of the few plants that survived.

Part B

Recent reclamation work on soils containing a high exchangeable sodium percentage (and the dispersed impermeable soil that results as salt is removed) involves the use initially of a high-salt-content water. If a salty water is used, much of the dispersion-causing exchangeable sodium is removed by exchange with the cations of the salt while the salty water keeps the soil flocculated and permeable. Once this removal of sodium is accomplished, the excess salt is removed from the soil by leaching (washing) with successively less salty waters, and finally, with normal water. This leaching procedure works well even using many kinds of soluble salts, as long as sodium is low, but it does involve the addition of extra salts and is expensive for large land acreages.

Two salts were used to leach the pots after first harvesting the plants grown following the first leaching attempt in Part A. Some pots were leached using calcium chloride (2% solution) and some were leached with 2 percent ammonium nitrate. Both salts were effective but should result in different soil conditions. Leaching with ammonium nitrate should leave large quantities of ammonium adsorbed to the exchange sites of the soil. Ammonium in the soil will not only nitrify and furnish more available nitrate, but the nitrification of the ammonium to nitrate will also increase soil acidity. Leaching with calcium chloride, on the other hand, should leave an alkaline, or near-neutral, calcium-saturated clay.

Soil mixtures were leached until the conductivity of water draining in most samples was less than 4 mmhos/cm. Several days time and often over a dozen additions of water was required after use of the salt solutions to get the conductivity low enough.

Part C

Because the leaching of the samples in Part B was inadequate (later tests of soil indicated some salt contents exceeding 4 mmhos/cm), it seemed best to recombine replicates and releach these pots.

The second extensive leaching was done by adding approximately 500 ml of 1 percent $Ca(NO_3)_2$ to leach the pots (containing about 1.6 liters of soil) and allowed to equilibrate or drain for about half an hour. Then about 500 ml of 0.2 percent $Ca(NO_3)_2$ was added to the soil and also allowed to equilibrate and/or drain. The soil was subsequently leached (washed) with about 200 ml increments of tap water (class 1 water, low SAR of 0.08 and low salt) until the leachate had a conductivity below 1 mmho/cm. The soil was allowed to equilibrate overnight, 100 ml of water added, and the conductivity of the leachate tested for salt. About 5 to 8 percent of the pots required a repeat of the concentrated $Ca(NO_3)_2$ salt water treatments (after first air drying and crushing the soil) followed by leaching because the soil became so slowly permeable before they were adequately leached.

Planting

Part A

Treble superphosphate (20.5 percent P) and sulfur coated urea (39.1 percent N) were mixed into the dry mud soil mixture of each pot in Part A. The pots were first planted July 7, 1975, with either 10 bean or 8 corn seeds, which about 7 to 10 days after germination in the laboratory were thinned to 6 bean or 6 corn seedlings. The pots were then put in the greenhouse, organized in a random design and maintained in suitable growing conditions as best they could be by correct watering.

Part B

Because so many treatments in Part A had poor growth, after the first harvest the soils were air dried, crushed, and large masses of roots removed. The samples were leached in the manner described in Part B of the "Reclamation Procedure." The leached pots were planted to corn and beans October 6, 1975 with the same procedure described in Part A except planting was done in the greenhouse.

Part C

After getting inadequate growth from the inadequately leached pots described in Part B in the "Reclamation Procedure," the same pots were air dried again and used for the last releaching procedure (Part C). The procedure for leaching was described in Part C of the "Reclamation Procedure." The pots after leaching were air dried and planted to corn and beans on June 14, 1976, with the same procedure which was mentioned in Part A except that pots were thinned to four plants rather than six as was used previously. Nitrogen, phosphorus, and potassium were added in irrigation water on July 1 as NH_4NO_3 and KH_2PO_4. Added in two increments during growth, the corn received a total of 200 kg N/ha and 200 kg P/ha; beans received 200 kg N/ha and 170 kg P/ha. One addition of 200 kg K/ha was added to both corn and beans.

Watering the Pots

Water was checked each day for all pots. Many of the treated soils developed hard crusts and a spongy gelatinous soil condition; watering was difficult to do to any known consistent moisture condition. In contrast the control plots, which were the soils without added muds, were easily watered to maintain an adequately moist soil; but many of the treated pots could not be allowed to dry adequately without developing very hard surface crusts. During germination this crust was an obvious inhibitor to emergence on many pots.

Plant Growth Conditions and Harvesting

The greenhouse temperature was automatically maintained at 24°C (75°F) during the daylight hours and at about 16°C (62°F) at night. Normal daylight through a plastic-covered greenhouse was the light source for growth.

Notes were taken on general plant appearance weekly only for soil mud mixtures in the first planting (Part A). After 45 days from each planting date, plants were photographed, harvested, and the fresh harvest weights were measured immediately. Plant materials were put in ovens at 65°C for several days, reweighed to obtain dry weights, and stored.

Laboratory Tests

When the soil-mud mixtures were dried and sieved, soil samples were collected with a vertical slice from each pot having the same treatment and composited as a single sample for analysis. Some of the characterization data for these samples are shown in Tables 7 and 8.

Electrical conductivity (EC) was determined on a saturated-soil-paste extract (Bower and Wilcox, 1965).

Soil pH of the original soil sample and soil-mud mixtures were done on a soil paste made with distilled water (Peech, 1965).

Moisture retention values at 1/3 bar and 15 bars of moisture suction were determined by the Utah State Soil Testing Laboratory using pressure plates. Moisture retained after applying 1/3 and 15 bars of air pressure approximate the water held at field capacity (soil fully wetted and drained of excess water) and at the permanent wilting percentage, respectively.

Organic matter content of soils was measured by the Walkley-black method of wet oxidation with potassium dichromate and sulfuric acid and back titration with ferrous sulfate (Allison, 1965). The

Table 7. Characterization data for the various treatments of high-rate soil-mud mixtures. See also Table 8

Sample code symbol	pH of soil paste	Electrical conductivity	Moisture values 1/3 bar	Moisture values 15 bar	Exchangeable sodium	Cation exchange capacity
		mmhos/cm	%	%	%	me/100 g
Dagor soil	6.2	1.6	36	16	0.5	42.4
DA-PCM-O-H[†]	6.4	95.0	30	15	4	23.3
DA-DTM-O-H	7.4	6.0	37	15	15	25.5
DA-HPLM-O-H	8.2	7.0	--[‡]	--	--	--
DA-LLSM-O-H	7.7	7.4	41	16	11	26.3
DA-LLPM-O-H	--	7.0	--	--	--	27.1
DA-DOEM-O-H	7.5	6.0	42	15	15	23.2
DA-MB-O-H	--	--	--	--	--	--
Kidman soil	7.4	0.8	17	6	1.1	12.2
KI-PCM-O-H	7.8	80.0	16	10	6	8.3
KI-DTM-O-H	--	3.5	2	7	20	11.7
KI-HPLM-O-H	9.2	6.7	24	9	--	--
KI-LLSM-O-H	8.8	4.1	24	9	30	10.5
KI-LLPM-O-H	8.5	7.5	24	8	4	10.1
KI-DOEM-O-H	8.4	6.5	26	11	21	10.5
KI-MB-O-H	--	1.4	21	6	11	9.1
Millville soil	8.0	1.1	21	7	7	11.7
MI-PCM-O-H	7.3	120.0	18	7	7	9.8
MI-DTM-O-H	--	4.0	25	8	46	11.7
MI-HPLM-O-H	9.6	4.4	--	--	--	--
MI-LLSM-O-H	8.4	11.0	24	9	35	10.5
MI-LLPM-O-H	8.6	6.5	27	9	17	11.7

Table 7. Continued

Sample code symbol	pH of soil paste	Electrical conductivity	Moisture values 1/3 bar	Moisture values 15 bar	Exchangeable sodium	Cation exchange capacity
		mmhos/cm	%	%	%	me/100 g
Millville soil (cont'd)						
MI-DOEM-O-H	8.6	6.5	26	12	32	10.5
MI-MB-O-H	--	1.4	23	6	11	8.5
Miamian soil	5.7	2.6	33	10	0.1	15.2
MN-PCM-O-H	6.2	95.0	27	11	7	11.1
MN-DTM-O-H	8.0	3.9	32	10	22	14.3
MN-HPLM-O-H	--	6.0	--	--	--	--
MN-LLSM-O-H	7.2	4.9	38	14	32	15.7
MN-LLPM-O-H	--	9.4	32	10	9	12.2
MN-DOEM-O-H	--	8.2	35	17	20	13.6
MN-MB-O-H	--	1.9	29	8	10	10.9
MU-2-74 soil	6.3	0.5	18	5	0.9	5.7
MU-PCM-O-H	6.8	120.0	17	7	11	5.7
MU-DTM-O-H	--	7.0	24	6	31	8.6
MU-HPLM-O-H	9.5	3.9	--	--	--	--
MU-LLSM-O-H	7.9	7.1	23	9	40	8.5
MU-LLPM-O-H	--	7.5	23	7	16	8.2
MU-DOEM-O-H	7.9	4.5	26	9	48	7.9
MU-MB-O-H	7.4	1.0	22	5	20	5.4

Table 7. Continued

Sample code symbol	pH of soil paste	Electrical conductivity	Moisture values 1/3 bar	15 bar	Exchangeable sodium	Cation exchange capacity
		mmhos/cm	%	%	%	me/100 g
North Carolina soil						
	5.2	1.4	16	9	1.6	7.4
NC-PCM-O-H	--	75.0	18	8	--	--
NC-DTM-O-H	6.1	4.0	24	10	29	10.1
NC-HPLM-O-H	9.5	2.8	--	--	--	--
NC-LLSM-O-H	7.2	14.0	25	10	21	9.1
NC-LLPM-O-H	--	8.0	21	9	13	8.8
NC-DOEM-O-H	6.9	12.5	29	19	32	8.5
NC-MB-O-H	6.3	2.0	20	8	12	7.0

†Code symbols are defined in Table 6.
‡A dash means no measurement was made.

Table 8. Some characterization data for various low-rate treatments of soil-mud mixtures. See also Table 7.

Sample code symbol	Moisture values 1/3 bar	15 bar	Exchangeable sodium	Cation exchange capacity
	%	%	%	me/100 g
Dagor soil	36	16	0.5	42.4
DA-PCM-L†	32	14	1.5	30.4
DA-DTM-L	34	13	5.8	31.6
DA-HPLM-L	36	16	--‡	--
DA-LLSM-L	33	15	5.9	32.6
DA-LLPM-L	34	16	3.3	32.6
DA-DOEM-L	35	20	0.6	36.2
DA-MB-L	31	13	1.4	32.6
Kidman soil	17	6	1.1	12.2
KI-PCM-L	15	6	1.5	11.1
KI-DTM-L	20	7	13.2	11.7
KI-HPLM-L	16	6	--	--
KI-LLSM-L	19	7	17.1	10.5
KI-LLPM-L	18	7	8.3	10.9
KI-DOEM-L	20	6	18.8	7.3
KI-MB-L	17	6	3.7	10.1
Millville soil	21	7	0.5	11.7
MI-PCM-L	19	6	3.2	9.8
MI-DTM-L	21	7	13.3	11.1
MI-HPLM-L	20	7	--	--
MI-LLSM-L	23	9	18.4	10.1
MI-LLPM-L	22	7	7.0	10.9
MI-DOEM-L	25	8	12.2	11.7
MI-MB-L	20	7	2.5	10.9
MU-2-74 soil	18	5	0.9	5.7
MU-PCM-L	19	6	5.6	7.2
MU-DTM-L	21	5	17.8	7.8
MU-HPLM-L	17	6	--	7.8
MU-LLSM-L	17	5	19.7	7.3
MU-LLPM-L	17	5	6.9	6.5
MU-DOEM-L	--	--	--	--
MU-MB-L	18	4	4.8	6.3
Miamian soil	33	10	0.1	15.2
MN-PCM-L	31	9	2.0	14.3
MN-DTM-L	33	9	10.5	15.3

(No other samples run)

†Code symbols are defined in Table

‡A dash means no measurement was made.

measured oxidizable organic matter was multiplied by 1.724 to obtain organic matter content.

Cation exchange capacity (CEC) values were measured by the Utah State University Soil Testing Laboratory using sodium acetate to exchange sodium onto the exchange sites, replacing the sodium with ammonium from ammonium acetate, and measuring the exchangeable sodium ion. Extractable potassium and sodium were measured in a neutral ammonium acetate extract.

Exchangeable sodium percentage was measured by extraction of the sodium (soluble sodium). From these measurements and CEC values, the percentage exchangeable sodium was calculated.

Photography

All photographs were taken using a prepared painted background board under natural diffused daylight inside the greenhouse. Kodacolor daylight film was used in a Spotomatic Pentax camera.

Statistical Design and Analyses

Since there are several independent variables, such as the six different soils, the seven mud mixtures, and the two proportions of soil-to-mud, which affect the crop yield (a dependent variable), a multiple linear-regression analysis was used in this study. This analysis gives the relationship between one dependent variable (dry weight or wet weight) and two of the independent variables (mud mixture and kind of soil).

After regression analysis indicated that yields were different between the variables (see Appendix III for overall statistics and examples), it was decided to use the Least Significant Difference (LSD) method to compare yields of treatment means with those of the controls.

Any treatment yield average value which is listed as significantly different than yields of control pots at the 99 percent level simply predicts that 99 times out of 100, the difference in yields is due to real treatment effects rather than to chance variation in yields. Large yield differences between replicates or controls (random error) increase the magnitude of the yield differences needed in order to have "statistical significance."

A brief procedure for getting the tables of analysis and the variance by using the program in the library of the B6700 computer is described in Appendix III.

RESULTS

Organization of the Results and Data

The results of this study include tabular data, graphed representations of the tabular material, statistical analyses, and photographic illustrations of growth. Only summary graphs and summary tables are presented in this results section; the detailed tabulations and most photographs are given in the appendices. The following list is a guide for locating the detail tabulations and photographs on items of interest.

Appendix I: The 1:4 Mud-Soil Studies: Data and Photographs

Appendix II: The 1:1 Mud-Soil Studies: Data and Photographs

Appendix III: Statistical Procedures and Examples

The presentation of the results will be in the following sequence, approximately, followed by the Conclusions section.

1. Germination Percentage and Growth Observations in General
2. The Nature of the Mud-Soil Mixtures
3. Plant Growth on 1:4 Mud-Soil Mixtures
4. Plant Growth on 1:1 Mud-Soil Mixtures
5. Effects of Salt-Water Leaching.

Germination Percentages and Growth Observations in General

This tabulation, much abbreviated, consists of the various observations made on the germination and growth of the beans and corn. Because plant yields are recorded, it was not felt useful to itemize any more detailed observations in the growth than the generalizations. Most visual observations were not distinctive nor informative as to specific problems or conditions.

1. Dagor soil. Dagor is a virgin (uncultivated) soil high in organic matter and well aerated (Honarvar, 1975). The germination of plants in control samples of this soil (average of 5 pots) was about 90 percent for corn and beans; the average plant height of plants in control the day before harvesting was 75-80 cm for corn and 45-50 cm for beans. The plants appeared to be normal during growth.

In the low-mud addition rate, the germination was 85-90 percent for beans and corn except in the PCM mixture, which had about 5 percent germination but the seedlings dried up after 3 weeks after reaching a height of 10-15 cm.

In the high-mud addition rate, the germination of beans and corn was about 80 percent except in the PCM samples which had no seeds germinate.

The soil surfaces of only LLSM and DOEM muds developed hard crusts; the other samples were normal.

2. Kidman soil. In this soil in all treatments including control plants grew more poorly than those in the Dagor soil.

The germination in control samples was about 80 percent for beans and about 90 percent for corn. The height of the bean plants at cutting time was about 40-45 cm, and in corn was 50-60 cm. In general, the corn plants looked better than bean plants. Most plants had the leaves develop a "cupped" appearance in beans and appeared scorched at the leaf tip of corn plants.

In the low-mud rates, the germination was about 80-90 percent except for the PCM treatment which had only 20 percent. The plant heights in the PCM treatment were only 5-10 cm and the plants died after 2 weeks. The growth in two treatments, mud base (MB) and lignite lignosulfonate potassium mud (LLPM), was similar to that in the controls. In the diesel oil (DOEM) treatment, bean leaves were chlorotic and the corn plants died within 3 weeks after planting. Particularly in the lignite lignosulfonate sodium mud (LLSM) treatments, the plants were not normal. Leaves in beans developed many white spots and in corn, purple stripes developed in the leaves.

At high-mud rates, no seeds of beans or corn germinated in the potassium chloride (PCM), and high pH lime mud (HPLM) treatments, and no beans germinated in the dichromate mud (DTM) treatment. Most of the corn plants that grew in the DOEM and DTM treatments and beans in the MB treatment had chlorosis, were small, looked abnormal, and died within three or four weeks. In the HPLM treatments, the leaves of corn developed strong purple coloration.

3. Miamian soil (Ohio). The Miamian silt loam is formed from calcareous loam till, but has a pH of about 5.6, is under beech, oak, hickory and maple forest, and has about 3.3 percent organic matter.

The germination in control samples was 80 percent for corn and beans. The height of bean plants was 45-50 cm and of corn was 70-75 cm. The plants in control samples looked normal.

Since there was not enough soil, the low-mud rates were omitted.

In the high-mud-addition rates, germination was about 80-85 percent except in the PCM treatment, which had no germination at all.

Plants in DOEM and HPLM treatments had about 30 percent reduction when compared with those in control samples.

4. Millville soil. This soil is a loam soil containing about 2 percent organic matter, a pH of 7.7, and 30 percent lime. Germination was good: corn was 95 percent; beans were 90 percent. The height of bean plants in control samples prior to harvest was about 40-45 cm and for corn was about 50-55 cm. This growth height in Millville control samples is about 20 percent less than the plants in control samples of the Dagor soil or the Miamian (Ohio) soil.

In the high-mud-addition rates, the beans in DOEM, DTM, and LLSM, and the beans and corn in PCM did not germinate at all. The plants in the MB treatment grew but were very poor; plant heights were only about 30 percent as large as controls. In the other treatments, the growth was about 25 percent as large as plants in control samples. Plants in all treatments having growth, except in LLPM and MB, died within 4 to 5 weeks.

5. MU-2-74 soil. This northern Utah soil collected from a leached layer (A2) under lodgepole pine forests is low in clay, in organic matter, and in nutrients, and is moderately acid. Plants did not grow as well in this soil as in the Dagor soil.

The germination was good, 90 percent for corn and beans. Also, the height growth was only fair, reaching only 50-55 cm for corn and 35-40 cm for beans, but the plant appearance was abnormal. Beans were chlorotic and leaves were cupped (puckered or curled). Although growth in the corn was better, leaves had scorched tips.

In the low-mud rates, germination was 90 percent except for the PCM treatment, which had only 50 percent. The plants in the PCM pots dried when they were only 5 to 10 cm tall (within 2 weeks).

In the high-mud-addition rates, the seeds of beans and corn in DOEM and PCM and beans in DTM did not germinate. Bean plants in DTM and HPLM grew to 10 to 15 cm tall and died. All bean plants were chlorotic and had cupped leaves; in corn, leaf tip scorch was common.

6. North Carolina soil. This strongly acidic clay loam from an uncultivated area in North Carolina was not limed, and plants in the control pots grew poorly. Perhaps the poor growth is because of aluminum toxicity, a common problem in strongly acidic soils.

Since there was not enough soil available for all treatments, the low-rate treatments were omitted. The germination in control samples was 85 percent and the heights reached at harvest time were 35-40 cm for beans and 50-55 cm for corn.

In the high-mud-addition rate, the germination was 85 percent except in the PCM treatments, which had no germination. In DOEM, HPLM, DTM, and LLPM treatments, plant growth was only one-fourth as great as those in the control samples. Beans in the DOEM treatment were chlorotic and soon died. Beans in the DTM treatment had small abnormal leaves; corn plants had scorched leaf tips.

The Natures of the Mud-Soil Mixtures

From Table 7, and the results of a previous study (Honarvar, 1975), the important components and factors which caused problems when the mud was mixed with soil can be categorized as follows:

1. Sodium hydroxide was added to all mud mixtures except the lignite lignosulfonate potassium mud (LLPM) which contained potassium

hydroxide instead of sodium hydroxide. Excess sodium can produce a sodic soil condition, especially when bentonite caly is present. The problem of sodic soils and their reclamation was discussed in the Review of Literature.

The exchangeable sodium percentage (ESP) of the various samples (Table 7) range from 4 to 48 for the high rates of mud addition. To avoid a dispersed soil condition, the ESP should be less than 12 to 15 so values below about 10 to 12 are normally good for normal growth. So the values of the ESP in most of these mud-soil mixtures make problems for plant growth. In the lignite lignosulfonate potassium mud (LLPM), in which potassium hydroxide is used in place of sodium hydroxide, the ESP was from 4 to 17. This is probably due to the sodium already present in the soils and on the bentonite clay used in the muds.

2. The pH in all mud mixtures was increased, with values ranging from pH 6.4 to 9.6. In Table 7 it is evident that the high pH lime mud (HPLM) had the highest pH of all mud mixtures. Values of pH for several samples are shown in Table 7. For Millville soil the pH was 9.6 when mixed with HPLM mud. Such a high value is not a good environment for most plants. In some acidic soils, the beneficial effect of increasing pH, as in the North Carolina and MU-2-74 soil, apparently was the cause of increased growth over that in controls.

3. The soluble salts, such as potassium chloride and, in some soils to a lesser degree, sodium dichromate, produce a saline soil with high electrical conductivity (EC). In Table 7 the EC of the saturation extract ranges from 1 to 120 mmhos/cm. The mud-base (MB) mixtures with the soils did not have any salinity problem. In contrast, the

potassium chloride mud (PCM) (Table 9) had the maximum salinity of all mud-soil mixtures, and it inhibited growth in most of the samples.

4. A hard surface crust occurred on many samples. The undesirable physical condition, such as a poorly structured impermeable soil, is the result of high sodicity. The water penetrates the soil slowly and the soil has poor aeration, and finally the soil forms a very hard crusted surface when dried. This condition of crusting occurred in most of the mixtures having 1:1 mud-soil ratios (Figures 4 and 5). Watering these soil samples was a slow process requiring frequent small applications. The Dagor soil with its very high organic matter content and high adsorptive capacity for exchangeable ions had the least crusted surfaces of all treatments and the MU-2-74 soil, with its non-aggregated fine sand and silt, developed very hard, slightly-cracking, dried surfaces in most mud mixtures.

Under field conditions, the mud-soil mixture conditions can be very different from those in the potted soil mixtures. In the field, the normal method of surface spreading the mud followed by incorporation of the air-dried or moist mud by tillage will usually not intimately mix the mud (with its sodium) into and through the soil. Large "clods" of soil will be intermixed with large "clods" of the mud. Thus drainage pathways through the soil portions, containing no mud, water infiltration into large cracks, and plant root growth in the soil-only portions may be expected in the field but not in the intimate mixing occurring in a small pot. The effects in the field should be less detrimental than appears in these greenhouse studies.

Figure 4. A typical view of soils and plants during midgrowth showing diesel oil emulsion mud (DOEM) treatments. Soils are crusted on top.

Figure 5. A close-up view of soil crusts in mixtures using lignite lignosulfonate sodium muds (LLSM). Note the plants that have died and dried up.

In some pots the spongy-like action of starch in holding excess water caused problems in watering the pots and conditions of apparent poor aeration existed.

Table 9. Salt content, as measured by electrical conductivity, in 1:1 mud-soil mixtures of potassium chloride mud (PCM) and each of the six soils

Soil	Untreated mud	With PCM mud added
	-------------mmhos/cm-------------	
Dagor	1.6	95
Kidman	0.8	80
Miamian	2.6	95
Millville	1.1	120
MU-2-74	0.5	120
North Carolina	1.4	75

Table 10. Soil paste pH values in 1:1 mud:soil mixtures of high pH lime mud (HPLM) with soils

Soil	Untreated mud	With HPLM mud added
	---------------pH---------------	
Dagor	6.2	8.2
Kidman	7.4	9.2
Miamian	5.7	--
Millville	8.0	9.6
MU-2-74	6.5	9.5
North Carolina	5.2	9.5

Initial pH of HPLM mud was 12.6.

Plant Growth on 1:4 Mud-Soil Mixtures

The use of a 1:4 mud-soil mixture (referred to as the "low rate") approximates the spreading of a 5-cm depth of mud on a soil, and, when it is dry, mixing it with about the top 20-cm depth of soil. This is a relatively dilute mixture. Spreading such a thin mud layer can be done, but it is probably a minimum depth of mud that can be conveniently spread without using some type of spraying technique.

Plant yields on the "low-rate" mixtures are given in Figures 8 and 9 and Tables 11 and 12. Actual average yield values (rather than as percentages of the controls are shown in the bar graphs of Figures 6 and 7. For more detail, individual pot values are given in Appendix I as Tables 18 to 25 and Figures 19, 20 and 21 Photographs to illustrate plant growth in these low-rate mixtures are also in Appendix I.

Statistical evaluation

Yield data of these and other treatments discussed in later sections was analyzed by multiple linear regression analysis. In this method, attention is centered on the dependence of one dependent variable (dry or wet weights of harvested plants) upon several independent variables (three variables in this study, soil kinds, mud mixtures, and addition rates). The hypothesis is that the yield does depend upon both the soil type and the mud mixture when tested only within one mud mixture. The control (untreated soil) was used as the "0 mud" treatment level in this experiment.

Since all the regression determinations (R^2) ranged from 0.88 to 0.95 for dry and wet weights of beans and of corn, the first model

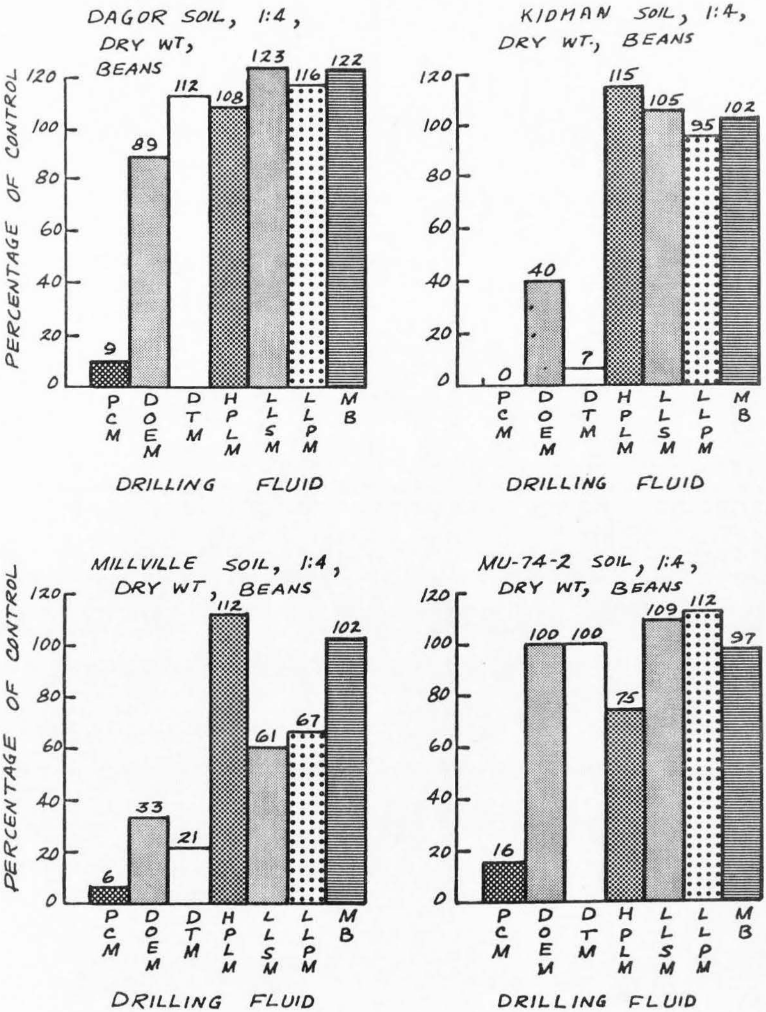


Figure 6. Dry-weight yields of green beans in 1:4 mud-soil mixtures of four soils, calculated as percentage of the growth produced on controls (soil only). Numbers above bars are percentages calculated as: Yield divided by the yield of control, all times 100 for percentage.

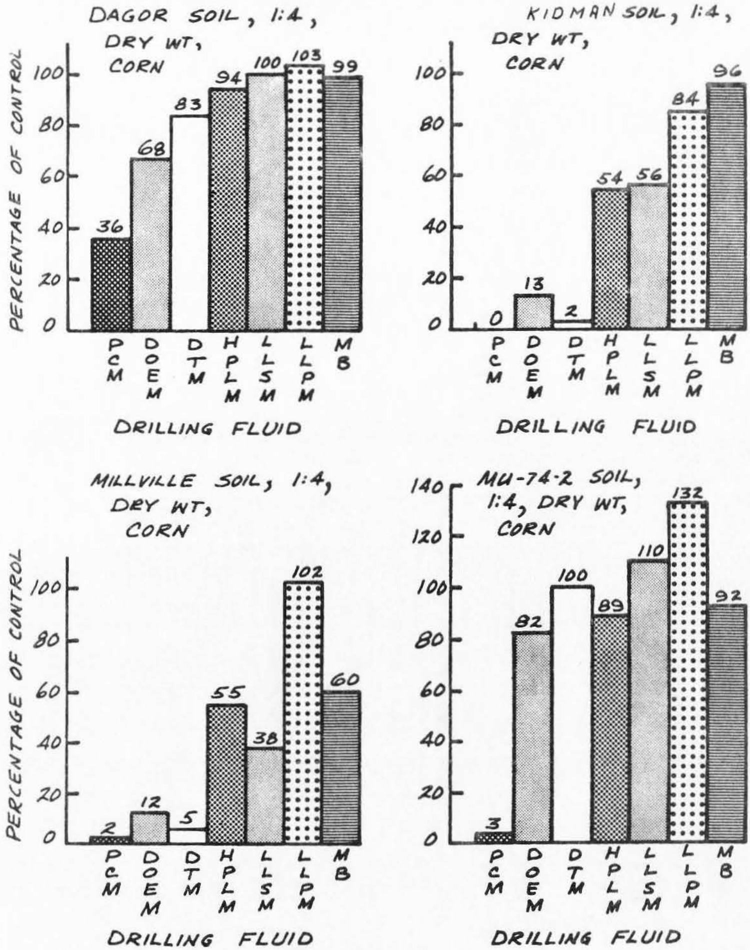


Figure 7. Dry weight yields of sweet corn in 1:4 mud-soil mixtures of four soils, calculated as percentage of the growth produced on controls (soil only). Numbers above bars are percentages calculated as: Yield divided by the yield of control, all times 100 for percentage.

Table 11. Statistical summary of the fresh yield weights of green beans and sweet corn (in grams per pot) grown in various mud and soil mixtures when the muds were added at the low rates (1:4 mud:soil ratio by volume).

Mud	Soil					
	Dagor	Kidman	Millville	MU-2-74	Miamian	No. Carolina
			Green Beans			
DOEM†	93.5**	21.5**	24.5**	60.5	0	No samples
DTM	120.5	5.0**	14.0**	44.0	119.7	
HPLM	114.5	70.5	84.5	34.5	--‡	
LLPM	125.5	75.0	47.5**	57.5	--	
LLSM	125.0	67.5	27.0**	50.0	--	
MB	135.5	67.0	81.0	41.0	--	
PCM	4.0**	0 **	0.5**	1.0**	0	
CONTROL†	119.3	63.6	78.8	48.6	123.6	
LSD (5%)	21.06	13.57	10.66	22.77	--	
LSD (1%)	25.58	16.48	12.94	27.66	--	
			Sweet Corn			
DOEM†	178.0	6.5**	3.5**	63.0	0	No samples
DTM	182.0	1.0**	3.0**	73.5	156.2	
HPLM	216.5	52.0**	36.0**	73.5	--‡	
LLPM	221.0	74.0	78.5	96.5§	--	
LLSM	203.5	53.5**	27.0**	79.5		
MB	209.0	83.0	27.5**	72.5	--	
PCM	84.0**	0 **	0.5**	0.4**	55.4	
CONTROL	212.4	88.6	74.1	66.2	146.4	
LSD (5%)	76.79	14.05	29.72	30.23	--	
LSD (1%)	93.27	17.07	36.10	36.73	--	

*Significant yield decrease at the 95% confidence level.
**Significant yield decrease at the 99% confidence level.
†Controls are averages of from 2 to 5 pots, depending on the particular soil. Treatments are averages of 2 replications.
‡No treatment used.
§Significant <u>increased</u> growth at the 95% confidence level.

Table 12. Statistical summary of the oven-dry yield weights of green beans and sweet corn (in grams per pot) grown in various mud and soil mixtures when the muds were added at the low rates (1:4 mud:soil ratio by volume)

Mud	Soil					
	Dagor	Kidman	Millville	MU-2-74	Miamian	No. Carolina
			Green beans			
DOEM†	14.0	3.5**	3.0**	7.0	0	No samples
DTM	18.0	0.5**	2.0**	7.5	18.8	
HPLM	17.0	11.0	13.0	5.0	--‡	
LLPM	18.0	9.0	7.5**	8.5	--	
LLSM	19.5	10.5	7.0**	8.5	--	
MB	19.0	9.5	11.5	7.5	--	
PCM	1.0**	0	0.5**	0.9**	0	
CONTROL†	15.8	9.8	11.8	8.0	20.1	
LSD (5%)	3.79	2.34	1.60	3.19	--	
LSD (1%)	4.60	2.84	1.94	3.88	--	
			Sweet corn			
DOEM†	17.5	1.0**	1.0**	7.0	0	No samples
DTM	21.0	0.1**	0.3**	9.0	22.3	
HPLM	24.0	6.0**	5.0**	8.0	--	
LLPM	27.0	10.0*	10.5	12.0	--	
LLSM	25.5	6.5**	4.0**	10.0	--	
MB	25.0	11.5	5.5**	8.0	--	
PCM	9.0**	0 **	0.1**	0.2**	7.8	
CONTROL	25.9	12.6	10.4	9.4	20.4	
LSD (5%)	10.21	2.04	3.24	3.96	--	
LSD (1%)	12.40	2.47	3.94	4.81	--	

*Significant yield decrease at the 95% confidence level.
**Significant yield decrease at the 99% confidence level.
†Controls are averages of from 2 to 5 pots, depending on the particular soil. Treatments are averages of 2 replications.
‡No treatment used.
§Significant increased growth at the 95% confidence level.

(multiple linear regression) was accepted as true, i.e., yields are affected by kinds of mud and by differences in soils and the relation between kind of soil and mud mixture on yield of beans and corn is linear.

The yield data in the statistical tables, Tables 11 and 12 in the text and 18 through 25 in Appendix I, illustrate that yield variations in the 1:4 mud-soil mixtures do occur and the variations are due to various of the added components and the different soils.

General evaluation of growth

The growth on Dagor soil, an excellent fertile soil, indicates the ability of Dagor to "buffer" or resist undesirable effects on these muds; similar mud treatments on other soils often resulted in reduced growth (Figures 8 and 9). On Dagor soil only the potassium chloride mud (PCM), because of its high salinity, caused a reduction in growth about 90 percent in beans and 60 percent in corn. Also on DOEM mixtures, reduction of fresh weights of beans was statististically significant (Tables 11 and 12). For the other mud mixtures with this soil, the yields were equivalent or higher than those of controls.

In the Kidman soil the DOEM, DTM, and PCM reduced bean growth significantly. The growth reduction of corn occurred on all mud mixtures except with the MB mud (Table 11 and 12). So the reduction in growth of corn was greater than for beans on samples of Kidman soil (Figures 8 and 9).

In the Millville soil all mud mixtures caused a statistically significant reduction in yields, except for the HPLM and MB mixtures planted to beans, and for the LLPM mixture planted to corn (Tables 11

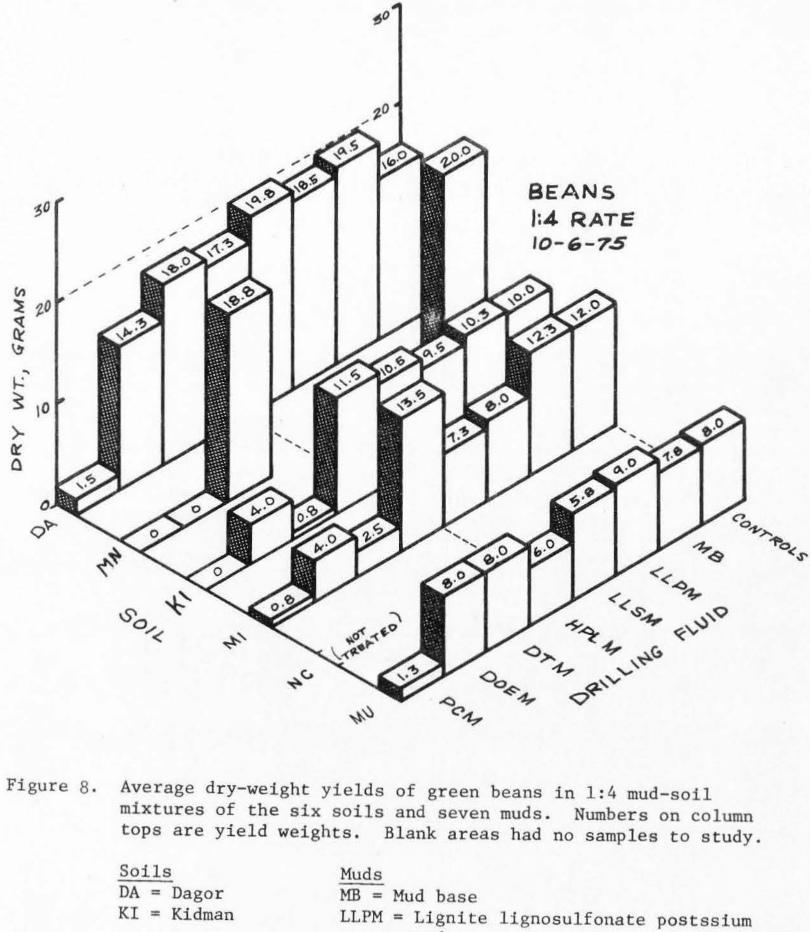


Figure 8. Average dry-weight yields of green beans in 1:4 mud-soil mixtures of the six soils and seven muds. Numbers on column tops are yield weights. Blank areas had no samples to study.

Soils	Muds
DA = Dagor	MB = Mud base
KI = Kidman	LLPM = Lignite lignosulfonate postssium mud
MI = Millville	LLSM = Lignite lignosulfonate sodium mud
MU = MU-2-74	HPLM = HIgh pH lime mud
MN = Miamian (Ohio)	DTM = Dichromate mud
NC = North Carolina	DOEM = Diesel oil emulsion mud
	PCM = Potassium chloride mud

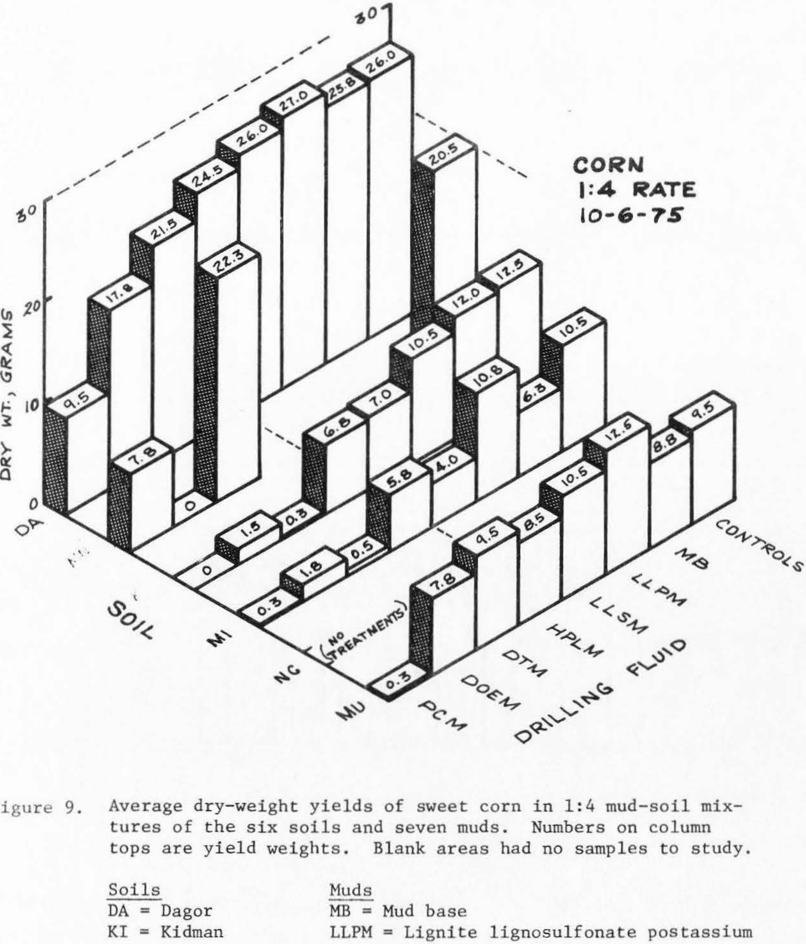


Figure 9. Average dry-weight yields of sweet corn in 1:4 mud-soil mixtures of the six soils and seven muds. Numbers on column tops are yield weights. Blank areas had no samples to study.

Soils	Muds
DA = Dagor	MB = Mud base
KI = Kidman	LLPM = Lignite lignosulfonate postassium mud
MI = Millville	LLSM = Lignite lignosulfonate sodium mud
MU = MU-2-74	HPLM = High pH lime mud
MN = Miamian (Ohio)	DTM = Dichromate mud
NC = North Carolina	DOEM = Diesel oil emulsion mud
	DCM = Potassium chloride mud

and 12). In this soil the growth reduction for corn was less than growth reduction of beans (Figures 8 and 9).

In the MU-2-24 soil, surprisingly, only the PCM treatment caused a statistically significant reduction in yield for corn and beans (Tables 11 and 12). In fact, in one case the yield was significantly increased by the addition of the mud. Addition of LLPM to the infertile and acidic MU-2-74 soil increased the fresh yield of corn. Probably it was the result of adding potassium as part of this mud to the soil. The soil-mud mixture had 205 ppm potassium, an adequate level for plants. Without the mud, the leached MU-2-74 would be expected to be low in potassium, since soil tests (Table 5) of the unleached soil show a marginal potassium level in the soil (154 kg K/ha).

Since inadequate quantities from North Carolina and Ohio (Miamian) were received to do all treatments, the 1:4 mud-soil mixtures were not set up.

Plant Growth in 1:1 Mud-soil Mixtures

The 1:1 mud soil mixtures (referred to as the "high rate") comparable to spreading a 15-cm deep mud layer on the soil and then mixing the dried mud (4 cm thick) with about a 15-cm depth of soil.

Plant yields on the "high rate" mixtures, relative to growth on the control samples, are illustrated in Figures 14 and 15, and Tables 13 and 14. Actual yield values are shown in the bar graphs of Figures 10, 11, 12, 13. For more detail, individual pot yield values are given in Appendix I as Tables 18 to 25, in Tables 26 to 28 in Appendix II, and in Figures 29 to 31. Photographs of growth in these high-rate mixtures are in Appendix II.

On the Dagor samples, the HPLM and PCM mixtures reduced bean yields

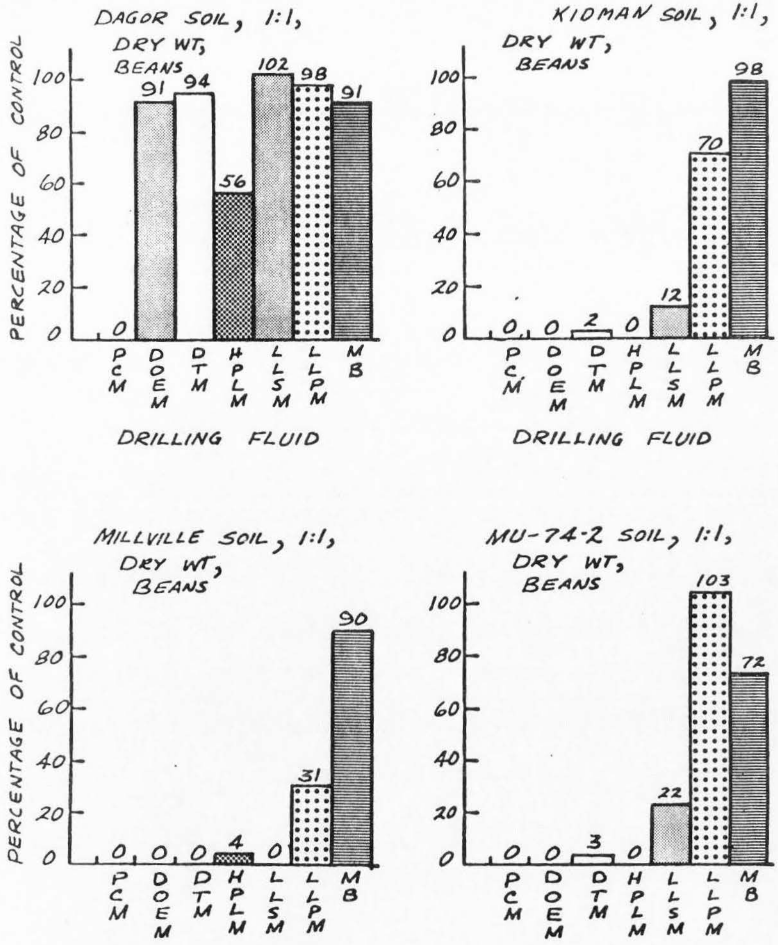


Figure 10. Dry-weight yields of green beans in 1:1 mud-soil mixtures of the four soils, calculated as percentage of the growth produced on controls (soil only). Numbers above bars are percentages calculated as: Yield divided by the yield of the control, all times 100 for percentage.

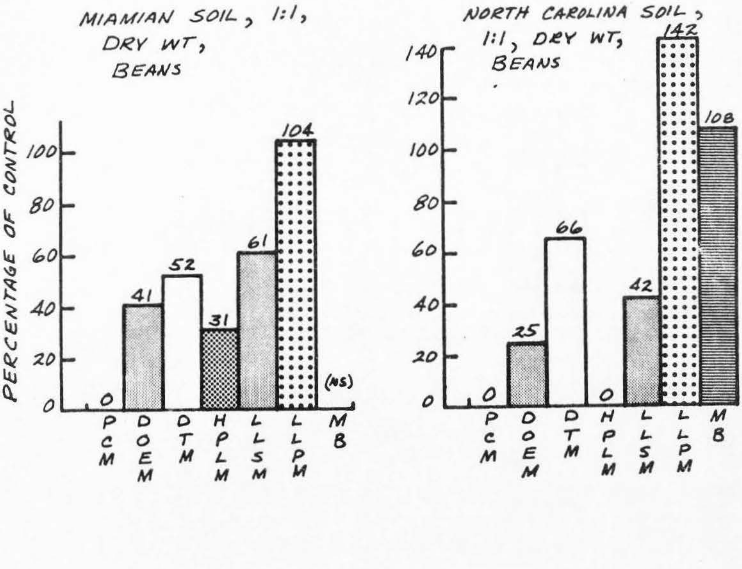


Figure 11. Dry weight yields of green beans in 1:1 mud-soil mixtures of Miamian and North Carolina soils, calculated as percentage of the growth on controls (soil only). Numbers above bars are percentages calculated as: Yield divided by the yield of control, all times 100 for percentage.

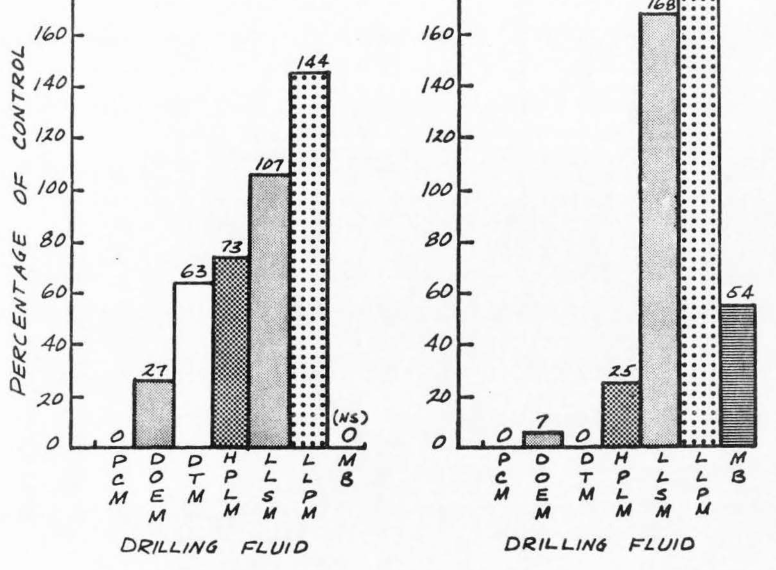


Figure 12. Dry-weight of sweet corn in 1:1 mud-soil mixtures of Miamian and North Carolina soils, calculated as percentage of the growth produced on the controls (soil only). Numbers above bars are percentage calculated as: Yield divided by the yield of the control, all times 100 for percentage.

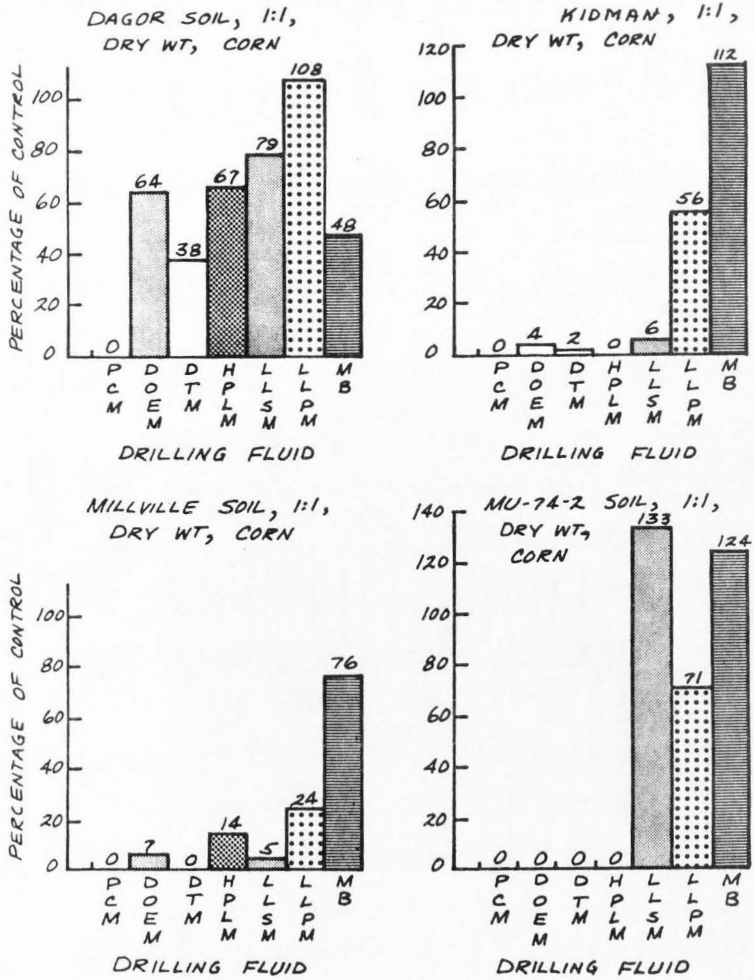


Figure 13. Dry-weight yields of sweet corn in 1:1 mud-soil mixture of four soils, calculated as percentage of the growth produced on controls (soil only). Numbers above bars are percentages calculated as: Yield divided by the yield of controls, all times 100 for percentage.

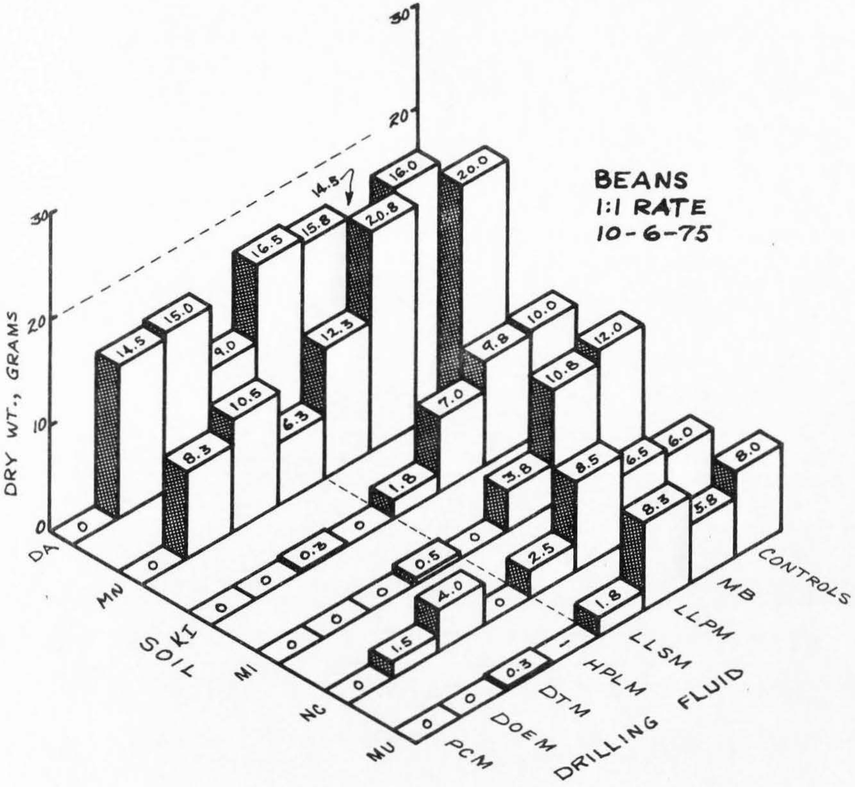


Figure 14. Average dry-weight yields of green beans in 1:1 mud-soil mixtures of the six soils and seven muds. Numbers on column tops are yield weights.

Soils

DA = Dagor
KI = Kidman
MI = Millville
MU = MU-2-74
MN = Miamian (Ohio)
NC = North Carolina

MB = Mud base
LLPM = Lignite lignosulfonate potassium mud
LLSM = Lignite lignosulfonate sodium mud
HPLM = High pH lime mud
DTM = Dichromate mud
DOEM = Diesel oil emulsion mud
PCM = Potassium chloride mud

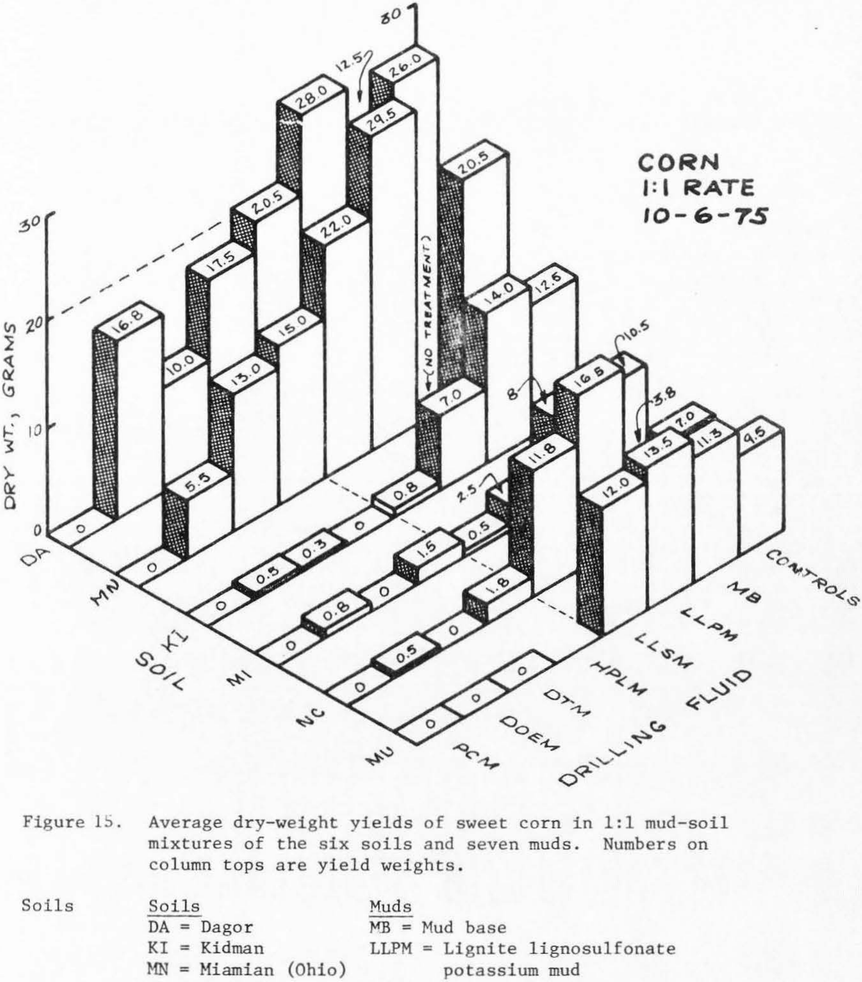


Figure 15. Average dry-weight yields of sweet corn in 1:1 mud-soil mixtures of the six soils and seven muds. Numbers on column tops are yield weights.

Soils

Soils	Muds
DA = Dagor	MB = Mud base
KI = Kidman	LLPM = Lignite lignosulfonate potassium mud
MN = Miamian (Ohio)	LLSM = Lignite lignosulfonate sodium mud
MI = Millville	HPLM = High pH lime mud
MU = MU-2-74	DTM = Dichromate mud
NC = North Carolina	DOEM = Diesel oil emulsion mud
	DCM = Potassium chloride mud

Table 13. Statistical summary of the fresh yield weights of green beans and sweet corn (in grams per pot) grown in various mud and soil mixtures when the muds were added at the high rates (1:1 mud:soil ratio by volume)

Mud	Soil					
	Dagor	Kidman	Millville	MU-2-74	Miamian	No. Carolina
			Green beans			
DOEM†	88.0**	0 **	0 **	0 **	47.0**	5.0**
DTM	95.5*	1.5**	0 **	1.5**	59.5*	0 **
HPLM	51.0**	0 **	1.5**	0.5**	34.0**	0 **
LLPM	98.0*	44.5**	21.0**	55.5	56.0*	52.0‡
LLSM	98.5	5.0**	0 **	5.0**	71.0	11.0**
MB	99.0	62.0	68.0	38.5	87.5	37.0
PCM	0 **	0 **	0 **	0 **	0 **	0 **
CONTROL†	119.3	63.6	78.8	48.6	123.2	32.9
LSD (5%)	21.06	13.57	10.66	22.77	56.60	9.52
LSD (1%)	25.58	16.48	12.44	27.66	29.90	11.95
			Sweet corn			
DOEM†	121.5**	2.0**	2.5**	0 **	47.5**	1.5**
DTM	86.5**	2.0**	0 **	0 **	93.0**	0 **
HPLM	129.0*	0 **	2.5**	9.4**	112.5	5.5
LLPM	105.0**	44.0**	16.0**	43.5	155.5	120.5‡
LLSM	157.5	2.5**	1.3**	73.5	168.5	75.0
MB	128.0*	96.5	52.0	86.0	142.5	28.0
PCM	0 **	0 **	0 **	0 **	0 **	0 **
CONTROL	212.4	88.6	74.1	66.2	146.0	49.5
LSD (5%)	76.79	14.05	29.72	30.23	36.95	37.31
LSD (1%)	93.27	17.07	36.10	36.73	46.08	46.86

*Significant yield decrease at the 95% confidence level.
**Significant yield decrease at the 99% confidence level.
†Controls are averages of from 2 to 5 pots, depending on the particular soil. Treatments are averages of 2 replications.
‡Significant <u>increased</u> yield at the 99% confidence level.

Table 14. Statistical summary of the oven-dry yield weights of green beans and sweet corn (in grams per pot) grown in various mud and soil mixtures when the muds were added at the high rates (1:1 mud:soil ratio by volume)

Mud	Soil					
	Dagor	Kidman	Millville	MU-2-74	Miamian	No. Carolina
			Green beans			
DOEM†	14.0	0 **	0 **	0 **	7.5*	1.0**
DTM	14.5	0.2**	0 **	0.3**	10.0	0 **
HPLM	8.5**	0 **	0.3**	0.3**	5.5**	9.0**
LLPM	15.5	7.0*	3.0**	8.0**	9.0	8.5‡
LLSM	16.0	0.9**	0 **	1.9**	11.5	2.5**
MB	14.0	9.0	10.0	5.5	18.5	6.0
PCM	0 **	0 **	0 **	0 **	0 **	0
CONTROL†	15.8	9.8	11.8	8.0	20.0	6.2
LSD (5%)	3.79	2.34	1.60	3.19	11.12	1.52
LSD (1%)	4.60	2.84	1.94	3.88	13.74	1.91
			Sweet corn			
DOEM†	16.0	0.4**	0.6**	0 **	5.5**	0.8*
DTM	9.5**	0.3**	0 **	0 **	12.5**	0 *
HPLM	17.0	0 **	1.0**	1.3**	14.5*	1.4
LLPM	13.5	6.5**	2.0**	6.4	21.0	16.0‡
LLSM	20.5	0.7**	0.4**	11.5	21.0	11.0
MB	12.0**	13.5	7.5	11.5	20.0	3.5
PCM	0 **	0 **	0 **	0 **	0 **	0 **
CONTROL†	25.9	12.6	10.4	9.4	20.7	6.8
LSD (5%)	10.21	2.04	3.24	3.96	5.12	5.81
LSD (1%)	12.40	2.47	3.94	4.81	6.39	7.29

*Significant yield decrease at the 95% confidence level.
**Significant yield decrease at the 99% confidence level.
†Controls are averagesof from 2 to 5 pots, depending on the particular soil. Treatments are averages of 2 replications.
‡Significant increased yield at the 99% confidence level.

and DTM, MB, and PCM mixtures reduced corn yields significantly (Figures 14 and 15).

On the Kidman and Millville soils the yield reduction was significant for all mixtures except for MB treatments (Tables 13 and 14). Yields on the MU-2-74 soil were reduced significantly with all mud mixtures except for beans on the LLPM and MB mixtures and corn on the LLPM, LLSM, and MB mixtures (Tables 13 and 14). Unlike treatments with the Dagor soil, the growth of corn in general was better than the growth of beans in this soil (Figures 10 and 13).

In the Miamian soil there was significant bean yield reductions in DOEM, HPLM, and PCM mixtures. Reduced yields of corn occurred on DOEM, DTM, HPLM, and PCM samples. The relative growth of beans, in general, was less than that of corn (Figures 11 and 12).

Bean growth on the North Carolina soil was reduced significantly for all mud mixtures except the MB and LLPM treatments. Corn growth was less than controls for DOEM, DTM, and PCM mixtures. Both corn and beans had significant yield increases on the LLPM mixture (Tables 13 and 14). This is probably because of increasing pH and the correction of potassium deficiency in this soil.

From the data, the soils when mixed with the drilling fluids are ranked in approximate order of increasing detrimental effects on beans and corn as follows:

Dagor soil--least detrimental when mixed with muds.

Miamian soil

North Carolina soil

Kidman soil

Mu-2-74 soil

Millville soil--most detrimental when mixed with the muds. It seems that either acidic soils or those soils with larger amounts or organic matter contents were less affected by the muds than the other soils. This may be an effect of numbers of exchange sites in reducing the sodium effect, of the total water retention, or of better structure.

When the individual effects of any mud on the oven-dry yields are considered, it is concluded that:

1. PCM with its high salt content completely inhibited germination in all soils (Table 14).
2. The MB did not reduce plant growth in any soils except corn growth on the one treatment in Dagor soil. Reduced growth on the Dagor soil is not expected and probably is an indication of the range of experimental error.
3. DOEM inhibited germination on half the beans and corn planted in its treatments. Only samples involving the Dagor soil had no significant growth reduction of beans and corn.
4. Seeds in DTM treated soils had only 70 percent germination. In the Dagor and Miamian soils bean yields were not reduced, but corn yields were reduced significantly in all soils (Table 14).
5. LLPM reduced yield significantly only in the Kidman and Millville soils. Contrastingly, yields on the North Carolina soil increased significantly. The improved yield is probably a combination of (1) correcting the potassium deficiency and (2) making the soil less acidic (Table 14). As given in Table 5, the North Carolina soil has only 80 kg/ha-15 cm

potassium, much less than half the approximate amount assumed to be necessary. In contrast, the mixture with the LLPM mud had 1,043 kg/ha-15 potassium--an excess.

6. Bean plant growth was reduced significantly in all soils by LLSM except in the Dagor and Miamian soils. But corn yields were reduced only in the Kidman and Millville soils. It Seems that the corn is less sensitive to Na than are beans.

Fresh yields, instead of oven-dry yields, produced similar conclusions for the soils, Mu-2-74, Kidman, Millville, and North Carolina, although for Dagor and Miamian soils, some treatments have changes in statistical significance (see Table 13 for more detail).

From the results obtained, it is concluded that in order of increasing detrimental effects on beans and corn, the muds rank approximately as follows:

Mud base (MB)--least detrimental

Lignite lignosulfonate potassium mud (LLPM)

Lignite lignosulfonate sodium mud (LLSM)

High pH lime mud (HPLM)

Diesel oil emulsion mud (DOEM)

Dichromate mud (DTM)

Potassium chloride mud (PCM)--most inhibitory.

The MB mud had consistently low salt and low exchangeable sodium content. The LLPM mud had low exchangeable sodium values also.

Effects of Leaching

A. Because there was not much growth in pots after the first leaching (Part A, using only tap water) no statistical analysis was performed on these data. With a low percentage germination (beans germinated in only 20 of 80 treatments and corn germinated in only 40 of 80 treatments), the treated samples were not better than untreated samples (mud + soil without leaching).

There are obvious reasons why leaching in Part A was not more effective in the "leached" samples in comparison to untreated ones (mud + soil without leaching).

1. Pots were planted before leaching began on the assumption that leached would be rapid enough to be finished in a day or two. However, because of low permeability of the mud-soil mixture, most soils were kept saturated several days for drainage and the inadequate aeration reduced germination later. About 75 percent of the pots planted to beans did not have any germination at all, and 50 percent of the pots planted to corn did not have germination.

2. The initial plan was to leach some treatments with six inches of water in increments to minimize salt and high exchangeable sodium problems of all the treatments involved, only some of the PCM mixtures were readily leached. After less than 500 ml of water had been added (of which about 1/3 or 3 cm percolated through) the majority of soil mixtures would percolate only 50 to 100 ml of water during 24 to 30 hours. Most mixtures could not be further leached after a few hundred ml percolated through. So the anticipated leaching was quite incomplete in all treatments, even those with the most permeable PCM mixtures.

3. Leaching the soils with high percentages of exchangeable sodium resulted in a dispersed soil which developed crusted surfaces, greatly hindering emergence and reducing the number of plants that emerged.

4. The dispersed soil has low permeability which causes a continual overly-wet soil condition and anaerobic fermentation which could have produced toxic substances.

5. In a few treatments, the incomplete leaching seemed to improve plant growth, compared with yields on control and untreated samples. The following tabulation lists the treatments in which treated samples had more yield than untreated soil (data not tested statistically):

Beans (g/pot)

Control yields	Untreated	Leached treatment
119.3	98.0	139.7

Corn (g/pot)

66.2	9.4	68.4
66.2	0.0	80.6
146.0	155.5	155.9
49.5	28.0	55.3

For the reasons just mentioned, it is difficult to conclude many facts from this part of the study. It is obvious, however, that without leaching plant growth on the materials is poor.

In Table 15, the number of pots which did not have corn and beans germinate is shown for each soil. In general germination and plant growth was good in both Dagor and Miamian soils; in the other mixtures in other soils germination or growth was poor. Also, germination in the MB mud was good in all soils and this mud had the least detrimental effect in all soils on plant growth. Then, LLPM mud was the second

Table 15. The total pots and the number of pots that did not germinate for both treatments (leaching with tap water) and untreated samples

Soil	Leached samples		Unleached samples	
	Total pots	No germination	Total pots	No germination
Grean beans				
Dagor	14	4	14	2
Kidman	12	12	74	6
Millville	12	11	14	0
MU-2-74	14	12	14	4
Miamian	14	9	14	2
North Carolina	14	12	14	5
Percentage not germinated		75%		33%
Sweet corn				
Dagor	14	2	14	2
Kidman	12	5	14	4
Millville	12	2	14	4
MU-2-74	14	9	14	6
Miamian	14	8	14	2
North Carolina	14	12	14	4
Percent not germinated		48%		26%

least detrimental.

B. In the second leaching procedure (Part B) which was the first procedure using salty water first, the soil mixtures were leached until the conductivity of water draining from samples in the leaching previous was less than 4 mmhos/cm. Unfortunately, the extent of final leaching with non-salty water was not complete enough. Although numerous samples had plant yields nearly as great as yields in controls, most of the samples were still yielding considerably less than controls. Surprisingly, there does not seem to be a consistent relationship between yields and soil salinity as measured on the saturated paste extract after harvest. It is known that leaching with the salt solution and with no additional fertilizer added, the yields could be influenced by inadequate fertility (nitrogen and potassium) or an unbalanced nutrition resulting from having mostly one ion (calcium), rather than a variety of ions, on the cation exchange sites.

Perhaps the major conclusion available from this portion of the study (although a statistical test was not made) is that leaching with salty water as done here can result in normal plant yields in any of the muds tested. Table 16 tabulates a number of individual yields obtained after this incomplete leaching and compares them to averages of yields from control samples. Also, see Figures 16 through 18. These results suggest that if the salt and physical problems can be eliminated, normal plant growth should be expected in these treatments.

Although this part of the study was not definitive, the following conclusions seem justified:

1. Leached samples of soils with PCM mud often yielded more plant growth than the controls.

Table 16. Individual fresh weight yields from various mud treatments compared with the appropriate average yields of control samples to illustrate that good growth was obtained on samples of many mud-soil mixtures.[a] Many of these samples still contained excess soluble salts (Part B, first salt water leaching).

Beans			Corn		
Mud	Yields		Mud	Yields	
used	Control	Treatment values	used	Control	Treatment values
	---grams per pot---			---grams per pot---	
PCM	82	78, 106, 99, 105	PCM	127	126, 103, 101
HPLM	82	66, 66	LLSM	127	74
LLPM	82	81, 59	LLPM	127	141, 108, 88
DOEM	82	66, 58	DOEM	127	76
PCM	62	59, 46	PCM	65	104, 105
HPLM	62	50	HPLM	65	44
LLSM	62	51	LLSM	65	41
LLPM	62	59			
PCM	51	66, 66, 44, 36	PCM	40	51, 35, 96, 39
LLSM	51	34, 33	LLPM	40	36
DTM	51	36, 36			
PCM	43	56, 39, 39, 34	PCM	39	87, 36, 54, 40
HPLM	43	70, 40	HPLM	39	36
LLSM	43	34	DTM	39	34, 33, 30
LLPM	43	31			
DOEM	43	38			
DTM	43	42, 38			
MB	43	72			
PCM	52	85, 63, 63, 63 68	PCM	53	48, 72, 47, 71
HPLM	52	49, 62, 56	HPLM	53	46, 42, 41, 42
LLSM	52	35, 55, 51, 38	LLPM	53	43
LLPM	52	44	DOEM	53	38, 34
DOEM	52	40	DTM	53	32
DTM	52	44			
PCM	52	94, 93	PCM	34	64, 76
HPLM	40	44, 28	HPLM	34	74, 37
LLSM	40	31	LLPM	34	43, 46, 35, 41
LLPM	40	35	DTM	34	43, 31

[a]Data within each bracket is from one soil. In order within horizontal lines, top to bottom the soils are Dagor, Kidman, Millville, MU-2-74, Miamian, and North Carolina.

2. "Normal" yields were obtained on many mud-soil mixtures following leaching with salty water and finally tap water.

3. Only on samples with DOEM mud was the plant yield always less than yields of the controls.

C. Four months after harvest of the Part B study, the third leaching procedure (Part C, second salt water leaching) was done. The soil mixtures were leached until the conductivity of drainage water, which was added after the wetted soil equilibrated overnight, was less than 1 mmho/cm. The plants germinated and grew well; the results are given in Table 17.

By comparing data in Table 14 (unleached samples) and that in Table 17 (leaching with diluted salty water in Part C), the following conclusions were obtained:

1. In the Dagor soil the plant growth was almost the same in leached and unleached samples except in the PCM treatment in which seeds did not germinate in unleached samples. After leaching, the plants in nearly all treatments grew well and yields were almost the same as those of control treatments.

2. In the unleached Kidman soil mixtures there was a significant reduction in plant yield in all treatments except those with the MB mud. After leaching corn yields were reduced only in the DOEM soil. There was, in addition, significant yield increases on the DTM, HPLM, LLPM, and PCM treatments with beans and on the HPLM and LLSM treatments in corn. Compared to the respective control yields, the leaching was more effective for treatments on Kidman soil than for those with the Dagor soil.

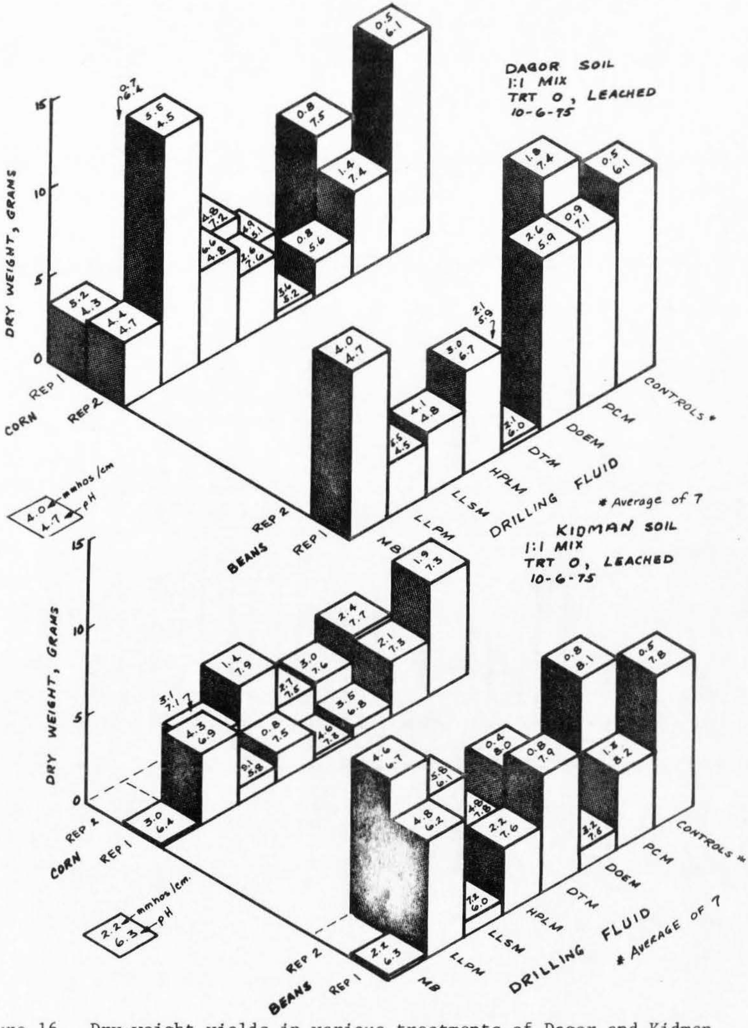


Figure 16. Dry-weight yields in various treatments of Dagor and Kidman soils in 1:1 mud-soil mixtures, after harvesting a previous crop, then leached with salt solution, and finally leached with tap water. Numbers in column tops are conductivity (salts) and soil pH, respectively. Some replications and treatments were not tested.

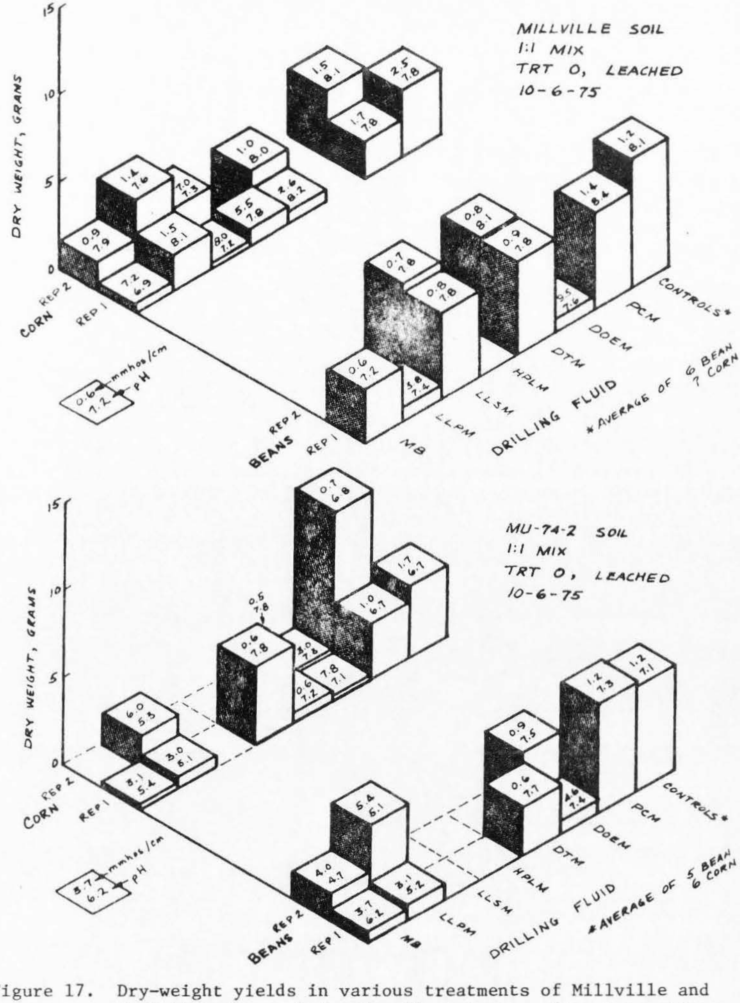


Figure 17. Dry-weight yields in various treatments of Millville and Mu-2-74 soils in 1:1 mud-soil mixtures, after harvesting a previous crop, then leached with salt solution, and finally leached with tap water. Numbers in column tops are conductivity (salts) and soil pH, respectively. Some replications and treatmets were not tested.

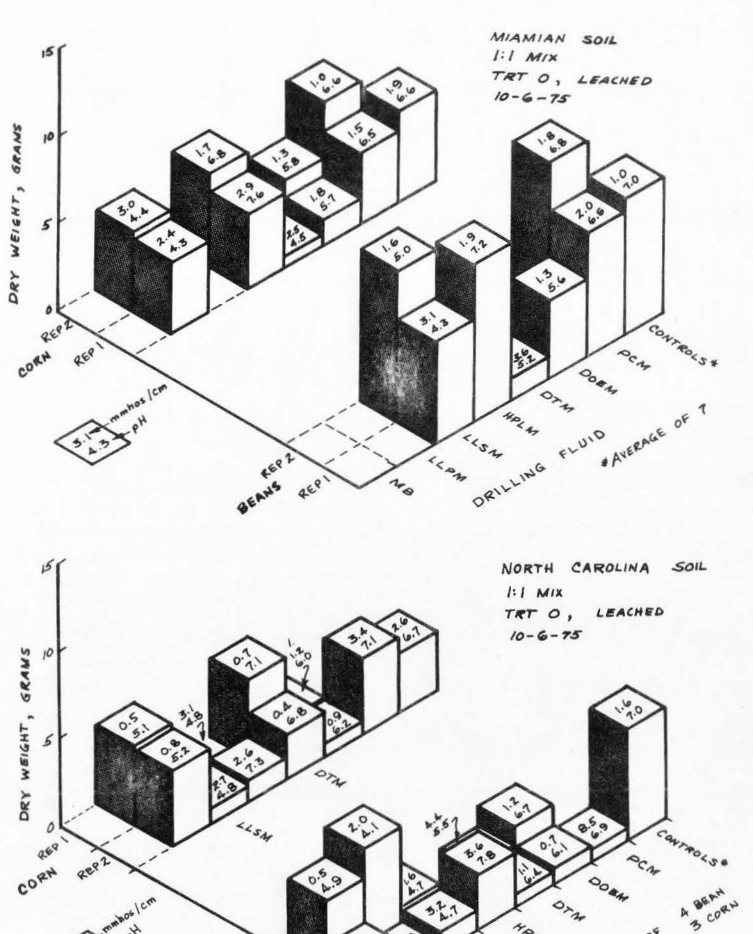


Figure 18. Dry-weight yields in various treatments of Miamian and North Carolina soils in 1:1 mud-soil mixtures, after harvesting a previous crop, then leaching with salt solution, and finally leaching with tap water. Numbers in column tops are conductivity (salts) and soil pH, respectively. Some replications and treatments were not tested.

Table 17. Statistical summary of oven-dry yield weights of green beans and sweet corn (in grams per pot) planted in 1:1 mud-soil mixtures, by volume, after samples were leached to remove salts and excess exchangeable sodium. Second salt water leaching (Part C)

Mud \ Soil	Dagor	Kidman	Millville	MU-2-74	Miamian	North Carolina
			Green beans			
DOEM	9.6**	8.8	5.5**	11.4	9.7	1.8*
DTM	13.5	12.0†	12.2	17.0	12.6	8.2
HPLM	11.5**	12.9††	11.5	14.0	9.7	6.8
LLPM	13.7	11.6†	11.2	13.9	13.0	10.3
LLSM	15.2	13.3††	14.4††	16.4	12.8	7.2
MB	15.9	10.6	9.9	14.2	13.5	6.9
PCM	15.1	14.2††	12.6†	16.3	12.1	11.8
Control§	15.2	8.7	9.2	15.0	9.2	7.8
LSD (5%)	2.34	2.44	3.49	5.13	5.11	4.3
LSD (1%)	3.24	3.45	3.82	7.15	7.2	6.11
			Sweet corn			
DOEM	23.3*	10.3**	6.2**	13.2**	15.2	7.9
DTM	20.2**	22.9	19.0	24.4	20.4	19.4
HPLM	26.7	25.5††	17.6	21.5	20.2	19.5
LLPM	25.4	23.0	12.6	27.4	25.1†	20.6
LLSM	28.5	23.6†	16.1	23.4	24.4†	21.6
MB	28.0	21.6	13.0	28.1	18.8	19.9
PCM	31.4	22.2	26.1††	33.4††	28.1††	21.3
Control§	28.8	20.1	16.6	25.5	18.8	15.7
LSD (5%)	4.10	3.39	6.89	7.22	4.91	7.97
LSD (1%)	5.67	4.69	9.53	10.06	6.09	11.34

§Controls are averages of from 4 to 10 pots, depending on the particular soil. Treatments are averages of 2 replications.
*Significant yield decreased at the 95% confidence level.
**Significant yield decreased at the 99% confidence level.
†Significant increased growth at the 95% confidence level.
††Significant increased growth at the 99% confidence level.

3. In the Millville soil there was a significant yield reduction in all unleached samples except those samples with MB mud. After leaching there was only a significant yield reduction for samples with DOEM mud. There were significant bean yield increases on samples with LLSM and PCM muds and corn yield increases on samples with PCM mud.

4. Samples of the MU-2-74 soil had significant yield reductions of beans from mud additions in all unleached samples except those with LLPM and MB muds, and reductions of corn in soils treated with LLPM, LLSM, and MB muds. After the leaching treatment, plants grew well in most mud-soil mixtures; only soils with DOEM mud had significant reduction in corn yield. There was, however, significant yield increases of corn in the PCM-soil samples.

5. In the Miamian soil there was significant yield reduction in all unleached samples except those with DTM, LLSM, and MB mud planted to beans and those with LLPM, LLSM, and MB muds planted to corn. After the soil mixtures were leached, most plants grew well in most samples. There were, in fact, significant yield increases of corn in the LLPM, LLSM, and PCM mud-soil mixtures that had been leached.

6. In samples of the North Carolina soil and the seven muds, there was a significant yield reduction of beans in all unleached samples except in the case of the MB mud; corn yields were normal in soils treated with HPLM, LLSM, and MB muds. The unleached samples did have significant yield increases for both beans and corn on the LLPM treatment. After leaching the mixtures, beans and corn grew well in all samples except beans in those treated with the DOEM mud.

7. The use of salty water followed by leaching with tap water for reclamation of the mud-soil mixtures was satisfactory for decreasing problems of swelling and soil dispersion and maintaining satisfactory hydraulic conductivity of the soil. Removal of soluble salts and exchangeable sodium were rapid and convenient.

CONCLUSIONS

Conclusions of previous work

The summary of results of the study made during the first year (1974) is referred to as Phase I, and was given on page 25. In phase I, researched previously by S. Honarvar, each mud component was studied individually. It was concluded that plant growth was reduced by several materials. The most inhibitory drilling fluid components were diesel oil, high concentrations of K Cl, high additions of NaOH, some starch, some lignosulfonates, and high levels of sodium dichromate.

In preliminary studies in Phase I, it was concluded that some obvious dominant effects of detrimental drilling fluid components were (a) excess soluble salts, (b) excess exchangeable sodium percentages, (c) possibly a high pH in some mixtures, and (d) undesirable physical conditions resulting from sodium and/or starches, gums, and bentonite.

There are other unidentified effects possible, such as toxic effects of chromium and phytotoxic effects of decomposition of some materials such as lignosulfonate; the latter effect is mentioned in the literature. These and other unidentified problems, if they exist as problems, which may cause growth reduction were not investigated.

Conclusions of present work

Phase II, the second year's study of drilling fluids effects on plant growth, was designed to use "typical drilling mud mixtures." The selection of muds was based on the results obtained from Phase I. The following conclusions are based on experimental evidence obtained in 1975 and 1976.

1. The soluble salt content in several soil-mud mixtures is enough to reduce or hinder most plant growth. Unleached potassium chloride muds (PCM) completely inhibited seed germination.

2. Over half of the soil-mud mixtures tested had exchangeable sodium percentages (ESP) too high (exceeding 20 percent) for maintenance of a desirable physical condition in the soils. The higher the sodium hydroxide (caustic) added to the mud, the greater the ESP is likely to be in a soil-mud mixture.

3. Some soil-mud mixtures involving the high pH lime mud (HPLM) had pH values of the final mixture high enough (pH 9.0-9.5) to be detrimental to growing plants.

4. In the mixtures with mud-soil ratios of 1:4 by volumes, all of the salty potassium chloride muds (PCM) hindered plant growth in the Dagor soil. On other soils the greatest plant growth reductions occurred with PCM, diesel oil emulsion muds (DOEM), and dichromate muds (DTM), although every mud used reduced growth in one soil or another.

5. Beneficial effects on growth occurred with the lignite lignosulfonate potassium mud (LLPM) on the acidic, low potassium MU-2-74 soil. It is speculated that the growth increase was a combination of improved (raised) pH and more available potassium..

6. A significant yield increase (beneficial effect) occurred when LLPM mud was mixed with the acidic, low-available-potassium North Carolina Soil. The beneficial effect is believed to be (1) raising the soil pH and (2) making adequate potassium available. The North Carolina soil is deficient in available potassium.

7. In 1:1 mud-soil mixtures (by volume), the mud base (MB) caused the least reduction in plant growth of all muds tested.

8. In order of increasing detrimental effects on green beans and sweet corn (the test plants), the muds mixed with soil at the 1:1 rate and with no reclamation treatment are ranked approximately as follows:

Mud base (MB)--least detrimental

Lignite lignosulfonate potassium mud (LLPM)

Lignite lignosulfonate sodium mud (LLSM)

High pH lime mud (HPLM)

Diesel oil emulsion mud (DOEM)

Dichromate mud (DTM)

Potassium chloride mud (PCM)--Most inhibitory

9. Most muds, when mixed with soils, caused soil dispersion which caused hard surface crusts to form as the mixture dried.

10. Attempts at leaching directly with tap water generally were not effective because of soil dispersion causing low permeability of the soil and mud mixtures.

11. Leaching first with salty water (2 percent $CaCl_2$ or 2 percent NH_4NO_3) in which subsequent leaching with tap water to a conductivity of drainage water to less than 4 mmhos/cm was not effective. Inadequate salt removal was believed to cause poor growth. However, the growth was better than on the samples in which leaching was attempted without first using salty water, and many samples had plant yields approaching those of the controls.

12. Leaching samples first with diluted salty water (1 percent $Ca(NO_3)_2$, then 0.2 percent $Ca(NO_3)_2$) and then leached with tap water to reduce equilibrated drainage water to a conductivity of less than

1 mmho/cm was effective. The plant growth improved in all mud mixtures, especially those with the PCM mud; samples with DOEM still had reduced plant yields.

13. The nature of the soil can subdue or enhance the effects of the detrimental mud components. The two soils shown to be low in available potassium--the North Carolina and the leached MU-2-74--were benefitted by the potassium in the two muds containing potassium, the PCM and LLPM. Acid soils, such as the Miamian and North Carolina would also be benefitted by the alkaline nature of the mud. Conceivably, quite sandy soils could be appreciably aided by the bentonite and organic materials of most muds. It should increase water retention and the cation exchange sites needed in Sandy soils to retain calcium, magnesium, and potassium available for plant use.

14. In contrast, plants on fine-textured soils which are already alkaline are more likely to have more marked reduction in growth when these muds are mixed with them. The alkalinity and soluble salts will be more noticeable. These soils are common in drier climates, say less than 20 inches annual precipitation.

15. Soils already high in organic matter (humus) and with moderate clay contents (10-20 percent) may, because of their surface area and good physical condition, minimize the effects of added salts and sodium. Greater water retention will dilute the salts and greater exchange capacities may buffer the effects of exchangeable sodium. Well-weathered soils of subtropics and tropics may be less sensitive to the sodium than are arid-region soils. This is because the kaolinite and sesquioxide (iron and aluminum hydroxide) clays found those climates are less easily

dispersed by sodium than is montmorillonite (bentonite) clay which predominates in drier climates.

16. Final summation 1. The major inhibiting effects of the drilling muds tested which lower plant growth are excess soluble salts, too high an exchangeable sodium percentage, and, at least temporarily, diesel oil.

17. Final summation 2. The drastic effects of salts and exchangeable sodium can be eliminated by the addition of some salt of calcium, magnesium, ammonium, or potassium followed by leaching to move salts out of the profile or into the deeper root zone area. The effects of diesel oil appear to be less severe and long-lived than the problems of salt or sodium. No evidence of other growth-inhibiting substances has been tested for or identified.

18. Final summation 3. Effects on plants of other drilling fluid components added for strata sealing or other purposes, such as starches, gums, fiber mixes, and various specialized organic preparations, have not been evaluated. The fact that they reduced plant growth when used alone (conclusion from Phase I, page 24) suggests that they should be further tested in mud mixtures.

19. Final summation 4. Drilling muds will be least detrimental on acid, leached soils high in organic matter and most detrimental on alkaline loam to clayey soils.

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APPENDIXES

Appendix I

The 1:4 Mud-Soil Studies, Data and Photographs

The following figures, tables, and photographs present additional individual sample values presented in several forms. The mixtures are 1:4 ratios by volume of mud to soil and data from some 1:1 ratio samples.

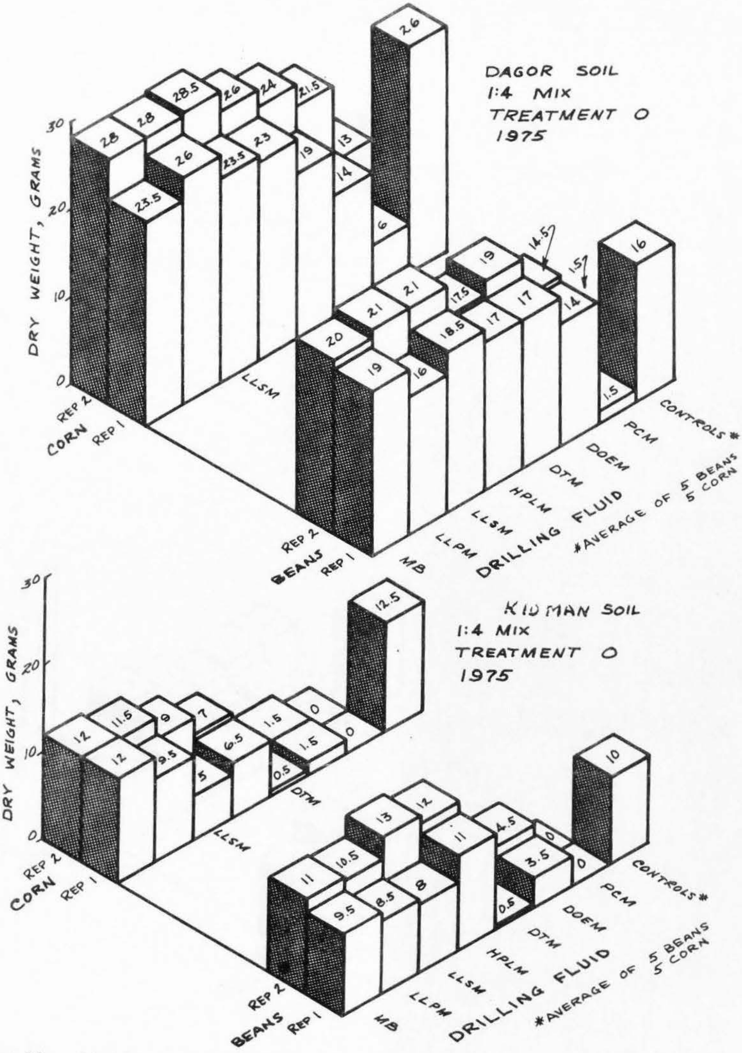

Figure 19. Yields of green beans and sweet corn in 1:4 mud-soil mixtures of Dagor and Kidman soils. Numbers on column tops are the dry-weight plant yields to the closese 0.5 g.

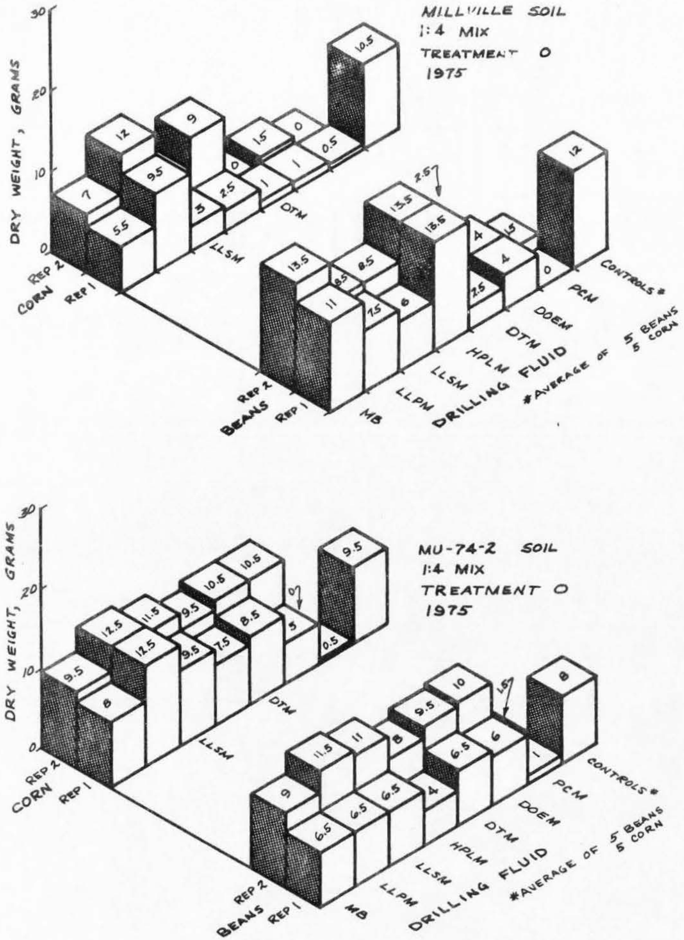

Figure 20. Yields of green beans and sweet corn in 1:4 mud-soil mixtures of Millville and MU-74-2 soils. Numbers on column tops are the dry-weight plant yields to the closest 0.5 g.

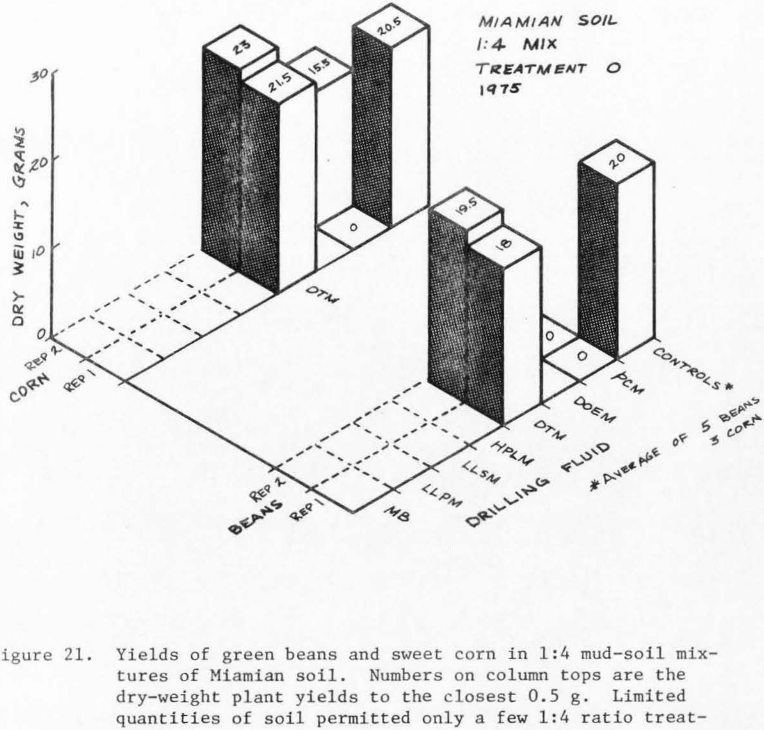

Figure 21. Yields of green beans and sweet corn in 1:4 mud-soil mixtures of Miamian soil. Numbers on column tops are the dry-weight plant yields to the closest 0.5 g. Limited quantities of soil permitted only a few 1:4 ratio treatments.

Table 13. Fresh yield weights of green beans (in grams per pot) grown on Dagor and Kidman soils to which various drilling mud components have been added, each at two rates.

Dagor soil

Materials	Low rates			High rates			Difference Low vs. high
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	95	92	93.5**	76	100	88.0**	5.5
DTM	130	111	120.5	101	90	95.5*	25.0*
HPLM	121	108	114.5	61	41	51.0**	63.5**
LLPM	135	116	125.5	95	101	98.0*	27.5*
LLSM	128	122	125.0	80	117	98.5	26.5*
MB	145	126	135.5	89	109	99.0	36.5**
PCM	7	1	4.0**	0	0	0.0**	4.0

Controls: 5 replications with average = 119.3

LSD (control vs. treatments) = 21.057 (95% confidence interval)
= 25.576 (99% confidence interval)

LSD (low vs. high = 25.168 (95% confidence interval)
= 30.57 (99% confidence interval)

Kidman soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	18	25	21.5**	0	0	0.0**	21.5**
DTM	4	6	5.0**	3	0	1.5**	3.5
HPLM	74	67	70.5	0	0	0.0**	70.5**
LLPM	63	87	75.0	44	45	44.5**	30.5**
LLSM	50	85	67.5	3	7	5.0**	62.5**
MB	62	72	67.0	63	61	62.0	5.0
PCM	0	0	0.0**	0	0	0.0**	0.0

Controls: 5 replications with average = 63.6
Treated groups: 2 replications

LSD (control vs. treatments) = 13.566 (95% confidence level)
= 16.478 (99% confidence level)

LSD (low vs. high) = 16.214 (95% confidence level)
= 19.695 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Table 19. Fresh yield weights of green beans (in grams per pot) grown on Millville and MU-2-74 soils to which various drilling mud components have been added, each at two rates.

Millville soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	24	25	24.5**	0	0	0.0**	24.5**
DTM	14	14	14.0**	0	0	0.0**	14.0*
HPLM	83	86	84.5	2	1	1.5**	83.5**
LLPM	50	45	47.5**	26	16	21.0**	26.5**
LLSM	38	56	27.0**	0	0	0.0**	27.0**
MB	77	85	81.0	63	73	68.0	13.0*
PCM	0	1	0.5**	0	0	0.0**	0.5

Controls: 5 replications with average = 78.8

LSD (control vs. treatments) = 10.657 (95% confidence interval)
= 12.944 (99% confidence interval)

LSD (low vs. high) = 12.738 (95% confidence interval)
= 15.472 (99% confidence interval)

MU-2-74 soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	85	36	60.5	0	0	0.0**	60.5**
DTM	52	36	44.0	3	0	1.5**	42.5**
HPLM	20	49	34.5	1	0	0.5**	34.0**
LLPM	72	43	57.5	54	57	55.5	2.0
LLSM	35	65	50.0	9	1	5.0**	45.0**
MB	35	47	41.0	34	43	38.5	2.5
PCM	1	1	1.0**	0	0	0.0**	1.0

Controls: 5 replications with average = 48.6
Treated group: 2 replications

LSD (control vs. treatments) = 22.774 (95% confidence level)
= 27.664 (99% confidence level)

LSD (low vs. high) = 27.221 (95% confidence level)
=33.064 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Table 20. Fresh yield weights of sweet corn (in grams per pot) grown on Dagor and Kidman soils to which various drilling mud components have been added, each at two rates

Dagor soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	166	190	178.0	166	77	121.5*	56.5
DTM	210	154	182.0	57	116	86.5**	95.5*
HPLM	226	207	216.5	140	118	129.0*	87.5
LLPM	213	229	221.0	210	0	105.0**	116.0**
LLSM	205	202	203.5	135	180	157.5	46.0
MB	215	203	209.0	114	142	128.0*	81.0
PCM	58	110	84.0**	0	0	0.0**	84.0

Controls: 5 replications with average = 212.4

LSD (control vs. treatments) = 76.786 (95% confidence level)
= 93.268 (99% confidence level)

LSD (low vs. high) = 91.777 (95% confidence level)
= 111.477 (99% confidence level)

Kidman soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	6	7	6.5**	0	4	2.0**	4.5
DTM	2	0	1.0**	4	0	2.0**	-1.0
HPLM	52	52	52.0**	0	0	0.0**	52.0**
LLPM	73	75	74.0	30	58	44.0**	30.0**
LLSM	63	44	53.5**	3	2	2.5**	51.0**
MB	81	85	83.0	99	94	96.5	-13.5
PCM	0	0	0.0**	0	0	0.0**	0.0

Controls: 5 replications with average = 88.6
Treated group: 2 replications

LSD (control vs. treatments) = 14.052 (95% confidence level)
= 17.068 (99% confidence level)

LSD (low vs. high) = 16.795 (95% confidence level)
= 20.4 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Table 21. Fresh yield weights of sweet corn (in grams per pot) grown on Millville and MU-2-74 soils to which various drilling mud components have been added, each at two rates

Millville soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	3	4	3.5**	1	4	2.5**	1.0
DTM	6	0	3.0**	0	0	0.0**	3.0
HPLM	13	59	36.0**	3	2	2.5**	33.5
LLPM	84	73	78.5	0	32	16.0**	62.5**
LLSM	20	34	27.0**	0	2	1.3**	25.7
MB	4	51	27.5**	49	55	52.0	-24.5
PCM	1	0	0.5**	0	0	0.0**	0.5

Controls: 5 replications with average = 74.1

LSD (control vs. treatments) = 29.718 (95% confidence level)
= 36.098 (99% confidence level)

LSD (low vs. high) = 35.52 (95% confidence level)
= 43.144 (99% confidence level)

MU-2-74 soil

Materials	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	87	39	63.0	0	0	0.0**	63.0**
DTM	71	75	73.5	0	0	0.0**	73.5**
HPLM	76	71	73.5	0.8	18	9.4**	64.1**
LLPM	102	91	96.5†	36	51	43.5	53.0**
LLSM	80	79	79.5	70	77	73.5	6.0
MB	69	76	72.5	89	83	86.0	-13.5
PCM	0	0	0.4**	0	0	0.0**	0.4

Controls: 5 replications with average - 66.2
Treated groups: 2 replications

LSD (control vs. treatments) = 30.235 (95% confidence level)
= 36.726 (99% confidence level)

LSD (low vs. high) = 36.137 (95% confidence level)
= 43.895 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.
†Statistically significant larger than controls at 95% confidence level.

Table 22. Oven-dry yield weights of green beans (in grams per pot) grown on Dagor and Kidman soils to which various drilling mud components have been added, each at two rates

Dagor soil

Materials	Low rates L_1	L_2	Ave.	High rates H_1	H_2	Ave.	Difference Low vs. High Ave.
DOEM	14	14	14.0	12	16	14.0	0.0
DTM	19	17	18.0	15	14	14.5	3.5
HPLM	17	17	17.0	0	8	8.5**	8.5**
LLPM	20	16	18.0	14	17	15.5	2.5
LLSM	18	21	19.5	13	19	16.0	3.5
MB	20	18	19.0	13	15	14.0	5.0*
PCM	1	1	1.0**	0	0	0.0**	1.0

Controls: 5 replications with average = 15.84

LSD (control vs. treatments) = 3.788 (95% confidence level)
= 4.601 (99% confidence level)

LSD (low vs. high) = 4.527 (95% confidence level)
= 5.499 (99% confidence level)

Kidman soil

Materials	Low rates L_1	L_2	Ave.	High rates H_1	H_2	Ave.	Difference Low vs. High Ave.
DOEM	3	4	3.5**	0	0	0.0**	3.5**
DTM	0.8	0.3	0.5**	0.5	0	0.2**	0.3
HPLM	12	10	11.0	0	0	0.0**	11.0*
LLPM	10	8	9.0	7	7	7.0*	2.0
LLSM	8	13	10.5	0.9	1	0.9**	9.6**
MB	9	10	9.5	9	9	9.0	0.5
PCM	0	0	0.0**	0	0	.0.**	0.0

Controls: 5 replications with average = 9.806
Treated group: 2 replications

LSD (control vs. treatments) = 2.338 (95% confidence level)
= 2.84 (99% confidence level)

LSD (low vs. high) = 2.794 (95% confidence level)
= 3.394 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Table 23. Oven-dry yield weights of green beans (in grams per pot) grown on Millville and MU-2-74 soils to which various drilling mud components have been added, each at two rates

Millville soil

Materials	Low rates L_1	Low rates L_2	Low rates Ave.	High rates H_1	High rates H_2	High rates Ave.	Difference Low vs. High Ave.
DOEM	3	3	3.0**	0	0	0.0**	3.0**
DTM	2	2	2.0**	0	0	0.0*	2.0
HPLM	13	13	13.0	0.3	0.7	0.3**	12.7**
LLPM	8	7	7.5**	3	3	3.0**	4.5**
LLSM	6	8	7.0**	0	0	0.0**	7.0**
MB	10	13	11.5	9	11	10.0	1.5
PCM	0	1	0.5**	0	0	0.0**	0.5

Controls: 5 replications with average = 11.774

LSD (control vs. treatments) = 1.600 (95% confidence level)
= 1.945 (99% confidence level)

LSD (low vs. high) = 2.191 (95% confidence level)
= 2.662 (99% confidence level)

MU-2-74 soil

Materials	Low rates L_1	Low rates L_2	Low rates Ave.	High rates H_1	High rates H_2	High rates Ave.	Difference Low vs. High Ave.
DOEM	9	5	7.0	0	0	0.0**	7.0**
DTM	9	6	7.5	0.6	0	0.3**	7.2**
HPLM	3	7	5.0	0.6	0	0.3**	4.7**
LLPM	11	6	8.5	7	9	8.0	0.5
LLSM	6	11	8.5	2	0.9	1.9	6.6**
MB	6	9	7.5	5	6	5.5	2.0
PCM	1	0.8	0.9**	0	0	0.0**	0.9

Controls: 5 replications with average = 8.026
Treated groups: 2 replications

LSD (control vs. treatments) = 3.194 (95% confidence level)
= 3.879 (99% confidence level)

LSD (low vs. high) = 3.817 (95% confidence level)
= 4.637 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Table 24. Oven-dry yield weights of sweet corn (in grams per pot) grown on Dagor and Kidman soils in which various drilling mud components have been added, each at two rates.

Dagor soil

Materials	Low rates L_1	Low rates L_2	Low rates Ave.	High rates H_1	High rates H_2	High rates Ave.	Difference Low vs. High Ave.
DOEM	14	21	17.5	19	13	16.0	1.5
DTM	24	18	21.0	7	12	9.5**	11.5
HPLM	25	23	24.0	18	16	17.0	7.0
LLPM	26	28	27.0	27	0	13.5	14.0*
LLSM	23	28	25.5	17	24	20.5	5.0
MB	27	23	25.0	9	15	12.0**	13.0*
PCM	6	12	9.0**	0	0	0.0**	9.0

Controls: 5 replications with average = 25.9

LSD (control vs. treatments) = 10.214 (95% confidence level)
= 12.405 (99% confidence level)

LSD (low vs. high) = 12.208 (95% confidence level)
= 12.405 (99% confidence level)

Kidman soil

	Low rates L_1	Low rates L_2	Low rates Ave.	High rates H_1	High rates H_2	High rates Ave.	Difference Low vs. High Ave.
DOEM	1	1	1.0**	0	0.9	0.4**	0.6
DTM	0.3	0	0.1**	0.6	0	0.3**	-0.2
HPLM	6	6	6.0**	0	0	0.0**	6.0**
LLPM	11	9	10.0*	5	8	6.5**	3.5**
LLSM	9	4	6.5**	0.8	0.6	0.7**	5.8**
MB	11	12	11.5	14	13	13.5	-2.0
PCM	0	0	0.0**	0	0	0.0**	0.0

Controls: 5 replications with average = 12.638
Treated group: 2 replications

LSD (control vs. treatments) = 2.036 (95% confidence level)
= 2.473 (99% confidence level)

LSD (low vs. high) = 2.434 (95% confidence level)
= 2.955 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Table 25. Oven-dry yield weights of sweet corn (in grams per pot) grown on Millville and MU-2-74 soils to which various drilling and components have been added, each at two rates.

Millville soil

Materials	L_1	L_2	Ave.	H_1	H_2	Ave.	Difference Low vs. High Ave.
DOEM	1	1	1.0**	0.4	0.8	0.6**	0.4
DTM	0.7	0	0.3**	0	0	0.0**	0.3
HPLM	2	8	5.0**	1	1	1.0**	4.0*
LLPM	12	9	10.5	0	4	2.0**	7.5**
LLSM	3	5	4.0**	0.3	0.5	0.4**	3.6
MB	5	6	5.5**	7	8	7.5	-2.0
PCM	0.2	0	0.1**	0	0	0.0**	0.1

Controls: 5 replications with average = 10.38

LSD (control vs. treatments) = 3.243 (95% confidence level)
= 3.940 (99% confidence level)

LSD (low vs. high) = 3.876 (95% confidence level)
= 4.708 (99% confidence level)

MU-2-74 soil

	Low rates			High rates			Difference Low vs. High
	L_1	L_2	Ave.	H_1	H_2	Ave.	Ave.
DOEM	10	4	7.0	0	0	0.0**	7.0**
DTM	8	10	9.0	0	0	0.0**	9.0**
HPLM	9	7	8.0	0.6	2	1.3**	6.7**
LLPM	12	12	12.0	4	8	6.0	6.0**
LLSM	11	9	10.0	12	11	11.5	-1.5
MB	7	9	8.0	12	11	11.5	-3.5
PCM	0.4	0	0.2**	0	0	0.0**	0.2

Controls: 5 replications with average = 9.4
Treated groups: 2 replications

LSD (control vs. treatments) = 3.958 (95% confidence level)
= 4.808 (99% confidence level)

LSD (low vs. high) = 4.731 (95% confidence level)
= 5.747 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.

Figure 22. Sweet corn growth in the six soil controls. Notice the leaf edge burn in MU-2-74, possibly a symptom of excess acidity.

Figure 23. Green bean growth in 4:1 soil-mud mixtures of Dagor soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Figure 24. Sweet corn growth in 4:1 soil-mud mixtures of Dagor soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

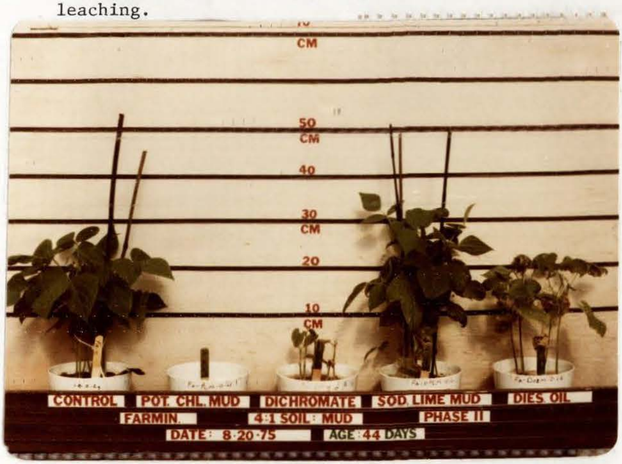

Figure 25. Green bean growth in 4:1 soil-mud mixtures of Kidman (FARMIN) soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Figure 26. Sweet corn growth in 4:1 soil-mud mixtures of Kidman (FARMIN) soil with mud, lignite lignosulfonate potassium mud, and the mud base. No other treatment; no leaching.

Figure 27. Green bean growth in 4:1 soil-mud mixtures of MU-2-74 soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Figure 28. Sweet corn growth in 4:1 soil-mud mixtures of MU-2-74 soil with lignite lignosulfonate sodium mud, lignite lignosulfonate potassium mud, and mud base. No other treatments; no leaching.

Appendix II

The 1:1 Mud-Soil Studies, Data and Photographs

The following figures, tables, and photographs present additional sample values presented in several forms. The mixtures are 1:1 ratios by volumes of mud to soil.

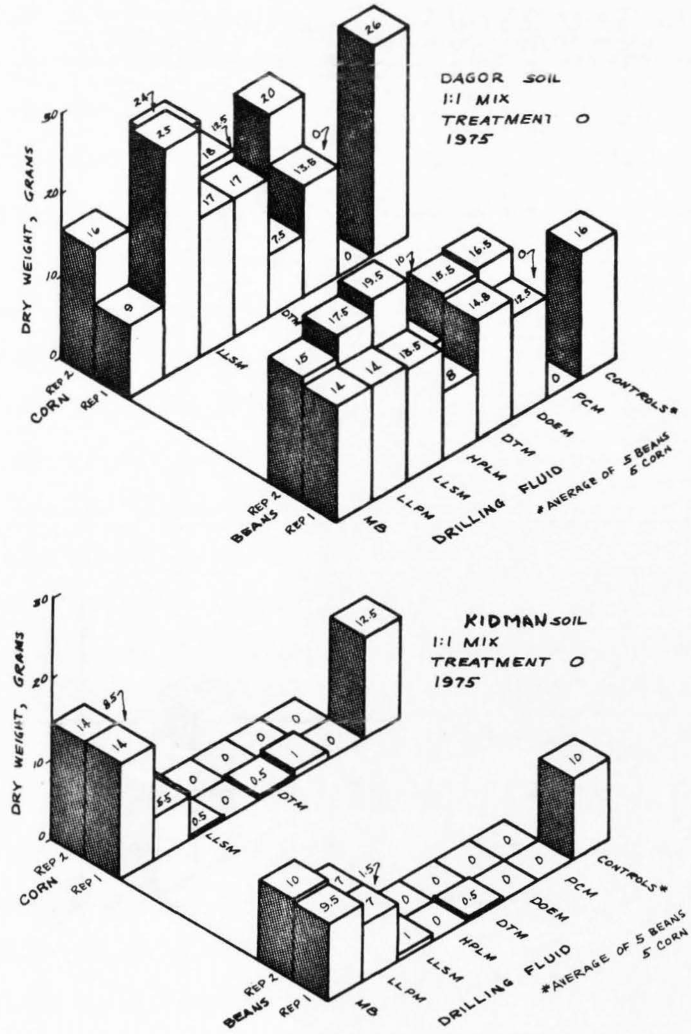

Figure 29. Yields of green beans and sweet corn in 1:1 mud-soil mixtures of Dagor and Kidman soils. Numbers on column tops are the dry-weight plant yields to the nearest 0.5 g.

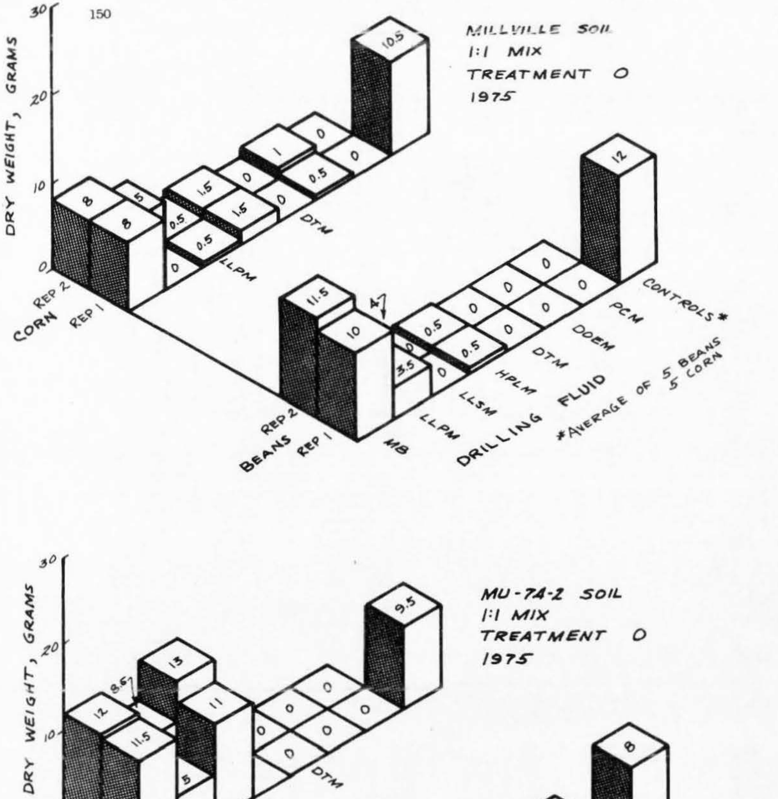

Figure 30. Yields of green beans and sweet corn in 1:1 mud-soil mixtures of Millville and MU-74-2 soils. Numbers on column tops are the dry-weight yields to the nearest 0.5 g.

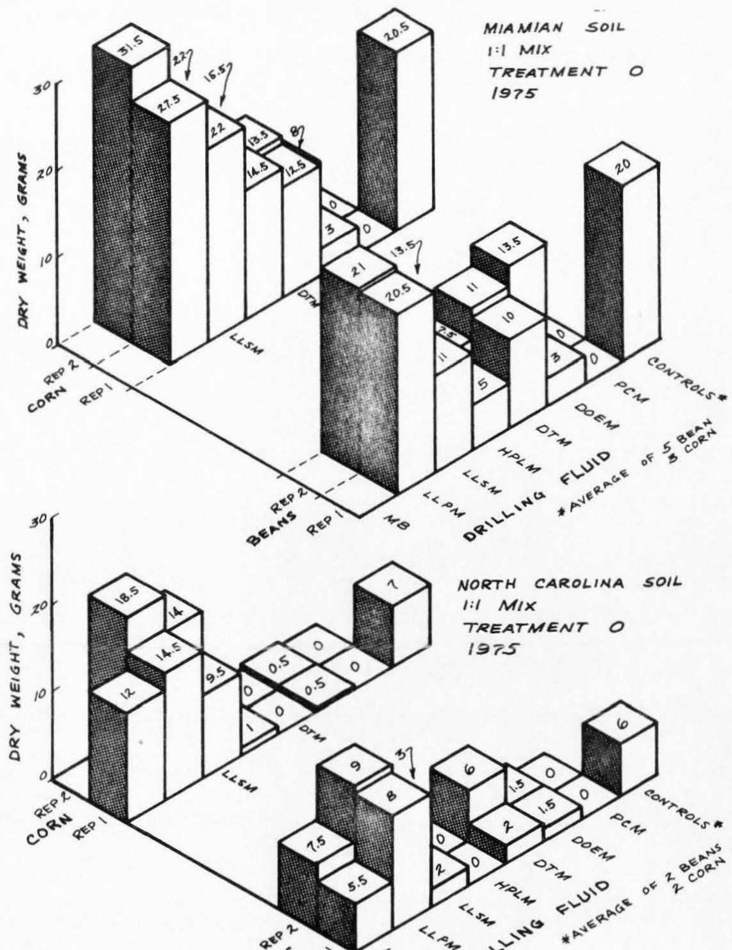

Figure 31. Yields of green beans and sweet corn in 1:1 mud-soil mixtures of Miamian and North Carolina soils. Numbers on column tops are the dry-weight to the nearest 0.5 g.

Table 26. Fresh yield weights of green beans (in grams per pot) grown on Miamian and North Carolina soils to which various drilling mud components have been added, only at the high rate.

Miamian soil

Materials	High rates		
	H_1	H_2	Ave.
DOEM	14	80	47.0**
DTM	64	55	59.5*
HPLM	21	47	34.0**
LLPM	9	103	56.0*
LLSM	82	60	71.0
MB	83	92	87.5
PCM	0	0	0.0**

Controls: 5 replications with average = 123.2
Treated groups: 2 replications

LSD (control vs. treatments) = 56.604 (95% confidence level)
= 69.899 (99% confidence level)

North Carolina soil

Materials	High rates		
	H_1	H_2	Ave.
DOEM	6	4	5.0**
DTM	0	0	0.0**
HPLM	0	0	0.0**
LLPM	48	56	52.0††
LLSM	9	13	11.0**
MB	44	30	37.0
PCM	0	0	0.0**

Controls: 2 replications with average = 32.9

LSD (control vs. treatments) = 9.516 (95% confidence level)
= 11.952 (99% confidence level)

*Statistically significant at 95% confidence level.
**Statistically significant at 99% confidence level.
††Statistically significant larger than controls at 99% confidence level.

Table 27. Fresh yield weights of sweet corn (in grams per pot) grown on Miamian and North Carolina soil to which various drilling mud components have been added, only at the high rate.

Miamian soil

Materials	High rates		
	H_3	H_4	Ave.
DOEM	76	19	47.5**
DTM	98	88	93.0**
HPLM	109	116	112.5
LLPM	165	146	155.5
LLSM	164	173	168.5
MB	149	136	142.5
PCM	0	0	0.0**

Controls: 3 replications with average = 146.0
Treated groups: 2 replications

LSD (control vs. treatments) = 36.951 (95% confidence level)
= 46.084 (99% confidence level)

North Carolina soil

Materials	High rates		
	H_3	H_4	Ave.
DOEM	1	2	1.5**
DTM	0	0	0.0**
HPLM	9	2	5.5*
LLPM	131	110	120.5††
LLSM	64	86	75.0
MB	56	0	28.0
PCM	0	0	0.0**

Controls: 2 replications with average = 49.5

LSD (control vs. treatments) = 37.31 (95% confidence level)
= 46.857 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.
††Statistically significant larger than controls at 99% confidence level.

Table 28. Oven-dry yield weights of green beans (in grams per pot) grown on Miamian and North Carolina soils to which various drilling mud components have been added, only in the high rate.

Miamian soil

Materials	High rate H_1	High rate H_2	Ave.
DOEM	2	13	7.5*
DTM	11	9	10.0
HPLM	4	7	5.5**
LLPM	1	17	9.0
LLSM	13	10	11.5
MB	12	25	18.5
PCM	0	0	0.0**

Controls: 5 replications with average = 20.03
Treated groups: 2 replications

LSD (control vs. treatments) = 11.125 (95% confidence level).
= 13.737 (99% confidence level).

North Carolina soil

Materials	High rate H_1	High rate H_2	Ave.
DOEM	1	1	1.0**
DTM	0	0	0.0**
HPLM	0	0	0.0**
LLPM	8	9	8.5††
LLSM	2	3	2.5**
MB	7	5	6.0
PCM	0	0	0.0**

Controls: 2 replications with average = 6.225

LSD (control vs. treatments) = 1.521
= 1.908

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.
††Statistically significant larger than controls at 99% confidence level.

Table 29. Oven-dry yield weights of sweet corn (in grams per pot) grown on Miamian and North Carolina soil to which various drilling mud components have been added, only in the high rate.

Miamian soil

Materials	High rate		
	H_3	H_4	Ave.
DOEM	8	3	5.5**
DTM	13	12	12.5**
HPLM	14	15	14.5*
LLPM	23	19	21.0
LLSM	21	21	21.0
MB	23	17	20.0
PCM	0	0	0.0**

Controls: 3 replications with average = 20.727
Treated groups: 2 replications

LSD (control vs. treatments) = 5.121 (95% confidence level)
= 6.387 (99% confidence level)

North Carolina soil

Materials	High rate		
	H_3	H_4	Ave.
DOEM	0.7	0.8	0.8*
DTM	0.0	0.0	0.0*
HPLM	2.0	0.8	1.4
LLPM	18.0	14.0	16.0††
LLSM	9.0	13.0	11.0
MB	7.0	0.0	3.5
PCM	0.0	0.0	0.0*

Controls: 2 replications with average = 6.765

LSD (control vs. treatments) = 5.809 (95% confidence level)
= 7.295 (99% confidence level)

*Statistically significant at the 95% confidence level.
**Statistically significant at the 99% confidence level.
††Statistically significant larger than controls at the 99% confidence level.

Figure 32. Green bean growth in 1:1 soil-mud mixtures of Miamian (Ohio) soil with lignite lignosulfonate sodium mud, lignite lignosulfonate potassium mud, and mud base. No other treatment; no leaching.

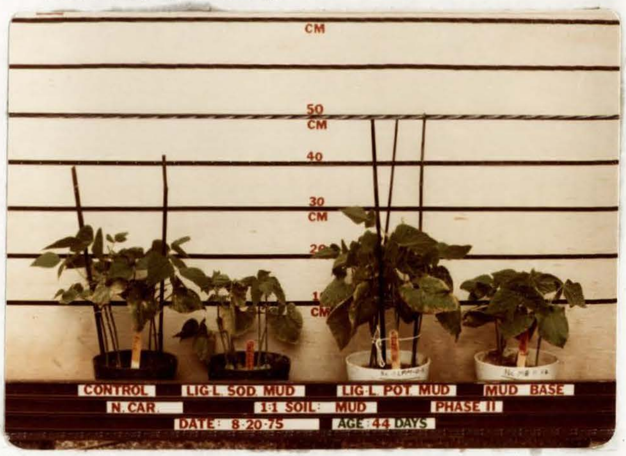

Figure 33. Green bean growth in 1:1 soil-mud mixtures of North Carolina soil with lignite lignosulfonate sodium mud, lignite lignosulfonate potassium mud, and the mud base. No other treatment; no leaching.

Figure 34. Green bean growth in 1:1 soil-mud mixtures of MU-2-74 soil with potassium chloride mud, dichromate mud, high pH mud, and diesel oil emulsion mud. No other treatment; no leaching.

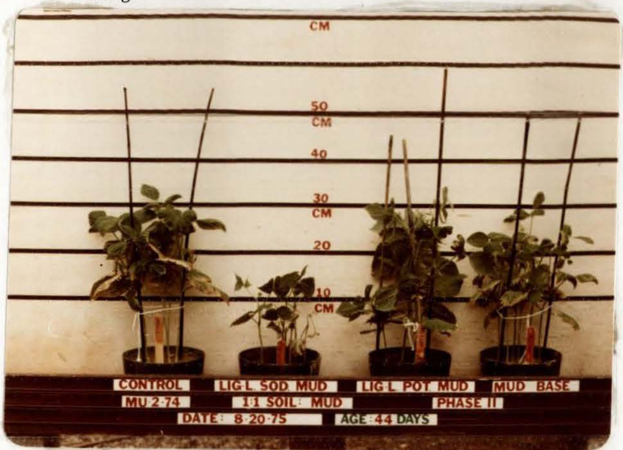

Figure 35. Green bean growth in 1:1 soil-mud mixtures of MU-2-74 soil with lignite lignosulfonate sodium mud, lignite lignosulfonate potassium mud, and mud base. No other treatment; no leaching.

Figure 36. Green bean growth in 1:1 soil-mud mixtures of Millville soil with lignite lignosulfonate sodium mud, lignite lignosulfonate potassium mud, and mud base. No other treatment; no leaching.

Figure 37. Sweet corn growth in 1:1 soil-mud mixtures of Miamian (Ohio) soil with lignite lignosulfonate sodium mud, lignite lignosulfonate potassium mud, and mud base. No other treatment; no leaching.

Figure 38. Green bean growth in 1:1 soil-mud mixtures of North Carolina soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Figure 39. Sweet corn growth in 1:1 soil-mud mixtures of North Carolina soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Figure 40. Green bean growth in 1:1 soil-mud mixtures of Miamian (Ohio) soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Figure 41. Sweet corn growth in 1:1 soil-mud mixtures of (Kidman) Farmington soil with potassium chloride mud, dichromate mud, high pH lime mud, and diesel oil emulsion mud. No other treatment; no leaching.

Appendix III

Statistical Procedures and Examples

Tabulations of the multiple linear regression analyses are listed for low and high mud addition rates without any leaching in this appendix. The values for error, mean squares, and other numerical data are given here.

Table 30. Summary of statistical analysis of oven-dry yields of green beans, Phase II, for low and high mud addition rates

Low addition rate

Source	df	SS	MS	F-test[a]
Model	31	113,051.73	3,646.83	
Soil	3	46,290.99	15,430.33	119.28**
Mud	7	44,362.78	6,337.54	48.99**
SXM	21	18,372.20	874.86	6.76**
Error	44	5,691.84	129.36	
Total	75	118,743.00	1,583.24	

Regression determination = R^2 = 0.952

High addition rate

Source	df	SS	MS	F-test[a]
Model	47	4,512.47	96.01	
Soil	5	1,659.35	331.87	36.00**
Mud	7	1,845.48	263.64	28.60**
SXM	35	635.57	18.15	1.97*
Error	63	580.23	9.21	
Total	110	5,093.00	46.30	

Regression determination = R^2 = 0886

[a]Refers to the level of significance.
*Means the source is significant at the 5% level.
**Means the sources are significant at the 1% level.

Table 31. Summary of statistical analysis of fresh green bean yields of Phase II, for low and high mud addition rates

Low addition rate

Source	df	SS	MS	F-test[a]
Model	31	113,051.73	3,646.83	
Soil	3	46,290.99	15,430.33	119.28**
Mud	7	44,362.78	6,337.54	48.99**
SXM	21	18,372.20	874.86	6.76**
Error	44	5,691.84	129.36	
Total	75	118,743.00	1,583.24	

Regression determination = R^2

High addition rate

Source	df	SS	MS	F-test[a]
Model	47	185,127.83	3,938.89	
Soil	5	63,123.60	12,624.72	61.76**
Mud	7	77,731.98	11,104.45	54.32**
SXM	35	23,004.93	657.28	3.21**
Error	63	12,876.57	204.39	
Total	110	198,004.40	1,800.04	

Regression determination = $R^2 = 0.939$

[a]Refers to the level of significance.
*Means the sources are significant at the 5% level.
**Means the sources are significant at the 1% level.

Table 32. Summary of statistical analyses of oven-dry yields of sweet corn, Phase II, for low and high mud addition rates

Low addition rate

Source	df	SS	MS	F-test[a]
Model	31	5,146.62	166.02	
Soil	3	3,358.71	1,119.57	177.3**
Mud	7	1,266.20	180.88	28.64**
SXM	2	279.15	13.24	2.10*
Error	44	277.64	6.31	
Total	75	2,524.75	72.33	

Regression determination = R^2 = 0.949

High addition rate

Source	df	SS	MS	F-test[a]
Model	47	6,850.25	145.75	
Soil	5	2,459.19	491.83	42.89**
Mud	7	2,442.86	348.98	30.43**
SXM	35	1,396.01	39.88	3.47**
Error	61	699.06	11.46	
Total	108	10,465.20	69.90	

Regression determination = R^2 = 0.949

[a]Refers to the level of significance.
*Means the sources are significant at the 5% level.
**Means the sources are significant at the 1% level.

Table 33. Summary of statistical analysis of fresh sweet corn yields of Phase II, for low and high mud addition rates.

Low addition rate

Source	df	SS	MS	F-test[a]
Model	31	373,471.57	12,047.47	
Soil	3	269,974.20	89,991.41	308.86**
Mud	7	65,345.05	9,335.00	32.03**
SXM	21	18,731.57	891.97	3.06**
Error	44	12,819.40	291.35	
Total	75	386,291.25	5,150.55	

Regression determination = R^2 = 0.967

High addition rate

Source	df	SS	MS	F-test[a]
Model	47	408,843.13	8,698.79	
Soil	5	160,403.50	32,080.70	49.87**
Mud	7	132,464.80	18,923.55	29.42**
SXM	35	75,165.14	2,147.57	3.33**
Error	61	39,233.37	643.17	
Total	108	448,076.88	4,148.86	

Regression determination = R^2 = 0.912

[a]Refers to the level of significance.
*Means the sources are significant at the 5% level.
**Means the sources are significant at the 1% level.

VITA

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