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Techniques to Reduce Soil Compaction in Reclaimed Soils

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Techniques to Reduce Soil Compaction in Reclaimed Soils

Final Report

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The views and conclusions contained in this document are those of the author/s and should not be interpreted as necessarily representing the official policies or recommendations of the U.S.Department of the Interior, Office of Surface Mining Reclamation and Enforcement, or of the United States Government.

FOREWORD

This report was prepared by the Department of Mining Engineering, the Department of Agricultural Engineering, and the Department of Agronomy of the University of Kentucky for the Office of Surface Mining Reclamation and Enforcement, under Contract Number GR896211. The contract was administered under the technical direction of Mr. Milton Allen acting as the Contracting Officer's Technical Representative. Ms. Debra E. Ball was the Contract Specialist for OSMRE. This report is a summary of the work that was performed during the period October 1988 to September 1991. We extend our grateful appreciation to OSMRE for supporting this research effort.

ABSTRACT

An innovative technique to reduce soil compaction and prevent recompaction simultaneously is presented for application to reconstructed soil on surface-mined land. This method employs conventional deep tillage technology in conjunction with pneumatic injection of organic soil amendments. The concept was tested extensively in the laboratory with a series of experiments performed on soil bins that had been compacted, treated, and then subjected to recompaction. The success of the technique was evaluated by analyzing various soil properties at each stage of the tests. The soil properties considered were bulk density, core penetrometer resistance, and hydraulic conductivity. There was also a field component of the investigation that monitored the bulk density of reclaimed prime farmland soil. The culmination of this effort is a conceptual design of a system that can be used for future prototype development.

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CHAPTER 1

BACKGROUND

Problem Statement

During the reclamation process, the soil is removed ahead of the pit(s) and is either stockpiled to await its replacement, or hauled immediately to graded spoil areas behind the pit. One consequence of soil transportation includes subsequent compaction. Generally, compaction produces an undesirable change in the physical properties of a soil. It is a common and potentially serious problem on reclaimed, mined lands. The degree of soil compaction is a function of applied pressure, soil moisture, and soil characteristics. The equipment used to transport the soil applies pressure to the surface, which results in an increase in soil density (Dollhopf and Postle, 1988).

A highly compacted soil reduces root growth, which in turn reduces crop yields. In addition, several soil properties change as a result of soil compaction. Soil density increases as the soil particles move closer together. The mechanical resistance to penetration increases, depending on moisture content and size of soil grains. The hydraulic conductivity is reduced due to an increase in compaction (Barnhisel, 1988). These changes occur as a consequence of soil movement and restoration. Minesoils generally show little or no soil structure throughout their profile. Structure may begin to appear in minesoil within 50 years (Dollhopf and Postle, 1988).

Soil compaction is an inevitable result of soil transportation due to the break-up of its structure. Several options exist for the mine operator when treating compacted soils. Deep tillage has been used frequently to correct physical problems inherent in a dense, massive soil (Barnhisel, 1988).

After an area has been tilled, it has a tendency to return to its original compact state due to subsequent cultivation practices, which require machinery traffic. In addition, some recompaction occurs due to natural settling. Overall, this results in a reduction of pore space that was created by deep tillage (Larney and Fortune, 1986, Kouwenhoven, 1985).

Objectives

The practice of injecting propping material into fractures created in reservoir rock has been used for many years in the oil and gas industry. The material maintains the fractures and allows for an increase in well productivity by increasing the permeability of the rock (Mader, 1989).

This research effort focused on deep tillage of prime farmland subsoil and subsequent recompaction. The primary objective of this study was to determine the effects of material injection on recompaction of a deep-tilled soil. It was hypothesized that the propping effects of the injected material will reduce, or prevent, the recompaction of a deep-tilled soil. Several materials, both organic and inorganic, were introduced with air under pressure during the tillage operations. The specific objectives of this study were:

1) To determine the feasibility of injecting various materials into the voids caused by deep-tillage with the use of air pressure;
2) To determine the effects of material injection on recompaction of a deep-tilled soil; and
3) To provide information for further study.

Literature Review

Soil is a three-phase system that consists of solid, liquid and gaseous phases. These phases can be referred to as the soil matrix, soil solution and soil atmosphere, respectively. The soil matrix includes minerals that make up the soil particles and organic matter that attaches to the mineral grains and binds them together into clusters. The soil solution contains water and nutrients (Hillel, 1980).

The U.S. Department of Agriculture defines prime farmland as "land that has the best combination of physical and chemical characteristics for producing food, forage and fiber" (Soil Conservation Service, 1983). The land uses could be cropland, rangeland (pasture and hay) or forestland. Residential land is exempt from this definition. Prime farmland has the quality, growing season, and moisture supply needed to produce high yields of crops when properly managed. It is permeable to water and air and has few or no rocks. The prime farmland definition is also applicable to lands used for mining, but regulatory authorities may grant exemptions for certain areas by one of two methods. The area may either be "grandfathered" due to the company's lease agreements on the area when the 1977 law was passed, or the area may be "negatively determined" (determined not to have been historically used for cropland). If a soil is designated as prime farmland but has not been managed as such, the soil may be treated as nonprime farmland soil in some cases (Commonwealth of Kentucky, 1985).

Soil Structure. A typical undisturbed soil will have macroscopic and microscopic structure. The macroscopic structure refers to the aggregation of the primary particles into clusters or peds. These are the individual units of soil that can be seen with the naked eye. The pore spaces located between the aggregates, or secondary particles, are termed macropores and the pore spaces located within the aggregate are termed micropores. The macroscopic structure is of importance in crop production since movement of air and water and root elongation occurs primarily in the macropores. The microscopic structure, which can only be seen with the aid of a microscope, is the structure of soil fabric. The mineralogical composition and its distribution determines the nature of the fabric. New soils have an undeveloped structure, which appears as weak lines of aggregation with few macropores. In contrast, mature soils have a well defined structure with obvious aggregation and distinct profiles. Subsoil tends to have larger aggregates than topsoil (Hillel, 1980).

Soil Compaction. Soil is, by nature, a variable and complex material. Soil compaction involves the interaction of many variables both internal and external. Internal factors consist of natural soil characteristics. External factors act upon the soil and generally are induced by soil handling or cultivation practices. A description of the diverse factors is provided by Albrecht and Thompson (1984). Those factors critical to this study are:

1) Moisture content and contact pressure;
2) Texture; and
3) Structure and organic matter.

The combination of moisture content and contact pressure, or compactive effort, determines to a large extent the resulting bulk density. The Proctor compaction test provides a relationship between moisture content and compactive effort. For a given compactive effort, there is a moisture content that results in the highest bulk density value. When applying a greater compactive effort, a lower moisture content results in a higher bulk density. Gravimetric mass moisture content was used throughout this report. It is defined as the mass of water divided by the mass of dry soil and is reported as a percentage (Hanks and Ashcroft, 1980).

Soil classification, or texture, is determined by the percentage of primary particles in each size category. The USDA textural triangle utilizes the ranges of particle size as shown in Table 1:

Table 1
USDA Particle Sizes

Fraction	Size (mm)
Gravel	>2
Sand	
Very Coarse	1.00 - 2.00
Coarse	0.50 - 1.00
Medium	0.25 - 0.50
Fine	0.10 - 0.25
Very Fine	0.05 - 0.10
Fines	
Silt	0.002 - 0.05
Clay	<.002

A particle size analysis gives only the proportion of different sized particles and not the arrangement of the particles with respect to each other. The texture determines the soil's ability to compact. If the soil is well-graded, there will be small particles to fill in the voids formed by the larger particles. A poorly graded soil will compact to a lower density due to insufficient smaller particles to fill in the void spaces (Gupta and Larson, 1979).

Soil structure and organic matter combine to produce favorable soil conditions for plant growth. Soil structure develops due to interacting physical, chemical, and biological factors. Wetting and drying causes the swelling and shrinkage of clay minerals. The formation of these desiccation cracks contributes to the development of aggregated structure. Clay minerals also act as a cementing agent inside the aggregate to give it strength, which promotes a well structured soil with definite planes of weakness between the peds (Hillel, 1980).

The biological agents of soil contribute to the development of structure. The macro soil animals increase aeration and drainage through the channels and burrows they develop. Macro animals such as earthworms have been effective in reducing bulk density in compacted subsoils (Larson and Allmaras, 1971). Macro soil animals macerate the plant litter they eat to provide food for the microorganisms. The microorganisisms produce positively and negatively charged particles that bind the soil together. Root secretions also act as a cementing material. Generally, organic matter increases the stability of intra-aggregate bonding (Hillel, 1980).

Reclaimed Mine Soil. The overall success of a crop grown on a relocated and compacted soil depends primarily upon its physical condition (Barnhisel, Powell, and Hines, 1986). This is determined by the physical properties of soil such as structure, bulk density, and resistance to mechanical penetration. Figure 1 shows a comparison of an undisturbed and a reclaimed soil. In an undisturbed soil, aggregates are separated by planes of weakness that are represented by the open spaces shown in the figure. These macropores allow for air and water transportation and root exploration. The removal and stockpiling of the soil, necessary for reclamation, breaks up these aggregates so that the original structure of the soil is destroyed.

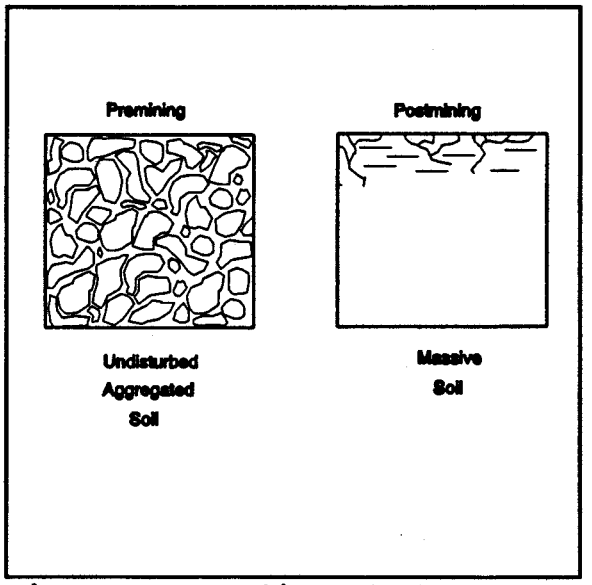


Figure 1 - Undisturbed, Aggregated Soil Versus Massive Soil

Upon removal and replacement, the soil is compacted with earth moving equipment to the extent that the original structure is destroyed and one massive unit of soil results. A crust is typically formed on the surface layers due to final grading and leveling of the soil. There are no apparent lines of weakness with the exception of desiccation cracks near the surface due to wetting and drying. This reduces water infiltration and transmission through the soil. Layers of excessively compacted soil develop at various levels in the profile due to the intensity of traffic. The pore space is greatly reduced by the loss of macropores. These factors combine to produce a soil with poor physical properties that inhibit root growth (Dollhopf, D.J. and Postle, R.C., 1988).

Methods of Alleviating Soil Compaction. Tillage is used as a corrective measure and serves a variety of purposes. It may be used to eradicate or control undesirable plants during crop production. The soil is typically inverted with a moldboard plow in order to prevent weed growth. Fertilizers, plant residues, mulch, and other soil amendments may be incorporated into the soil by inversion (Gill and Vanden Berg, 1968). Shallow tillage may also be used to insert seeds into the soil.

In the case of dense, massive soils, the physical condition can be modified. This is accomplished by loosening and breaking up the soil so that water and air may move more freely. Tillage greatly increases the macroporosity, at least temporarily (Hillel, 1980).

Instead of inverting the soil, as done in conventional tillage at shallow depths, deep tillage breaks the subsoil with a knifelike instrument. Deep tillage is performed to remedy a particular situation. On minesoils during the reclamation process, deep tillage is performed typically to reduce compaction (Barnhisel, 1988).

When deep tilling is in order to loosen the soil to enhance crop production, the performance is typically based on the following requirements (Gill and Vanden Berg, 1968):

1) Tillage must reduce clods to a desirable size;

2) The energy applied to the soil must be used efficiently in breaking up the soil;
3) The power requirements per unit of tilled soil must be low; and
4) The machine capacity must be high.

The first two items can be controlled by deep tilling at a moisture content that optimizes the shattering of the soil. Generally, a dry soil will shatter better than a wet soil. However, massive soils tend to break up into large clods regardless of the moisture content (Cooper, 1971). The third item depends upon the physical properties of the soil, such as density and strength. A highly compact soil will require more power input (Chancellor, 1977). The last item is machine dependent.

Deep tillage has been used to control wind erosion where sandy soils are underlain by clay subsoil. In this case, deep tillage increased the clay content of the surface layer and acted as a binding agent to prevent topsoil erosion (Foth and Turk, 1972).

There are several natural methods that can be employed to alleviate excessive compaction. Deep rooting legumes such as alfalfa, sweet clover, lespedeza and birdsfoot trefoil are well suited for revegetation purposes on reclaimed mine soil. In addition, legumes increase soil nitrogen and promote the growth of microorganisms that work in the organic matter (Grandt, 1988).

Freezing and thawing of the soil results in loosening. As ice crystals form, water from the local area moves toward the crystals. The water then freezes and the ice crystal develops into a lens shape and attracts water from the surrounding area. This causes the immediate pore space to be used up. Particle displacement occurs due to the growth of the ice formation. This results in expansion of the soil in the area of lens formation (Larson and Allmaras, 1971). The benefits of this method are limited to the frost zone, which in many areas does not extend to the depth of subsoil replacement (McCarthy, 1982).

Deep Tillage Failure Patterns. Four types of soil failure can occur when forces are applied: shear, plastic flow, compression, and tension. The soil's initial condition affects the mode of failure. The reaction of the soil will depend upon the bulk density, soil texture and moisture content.

When a ripper is pulled through the soil, the resulting failure is assumed to follow the Mohr-Coulomb failure criterion when moisture contents are less than the plastic limit (Stafford, 1979; Godwin and Spoor, 1977). This type of shear failure is described as crescent-shaped. The soil moves forward, upward and fans out. The crescent failure increases with increasing working depth until, at a certain depth, termed the critical depth, the soil at the ripper base will begin to flow forward and sideways only (lateral failure). The volume of soil fails along a plane of weakness developed when the combined applied stress exceeds the strength. The location of the failure plane, or slip line, is determined by the soil's characteristics, such as angle of internal friction, moisture content, bulk density and texture (Godwin and Spoor, 1977). The intersection of the shear failure (slip line) and the ripper defines the critical depth. The critical depth is sensitive to changes in soil characteristics such as density, angle of internal friction and moisture content as well as ripper configuration and operating variables.

The phenomenon of plastic flow can be observed when a ripper moves through a wet clay. Instead of shattering and developing distinct shear failure planes that can be seen on the surface, the soil flows around the subsoiler and remains a continuous mass (Gill and Vanden Berg, 1968; Stafford, 1979). The boundary between the two types of failure occur near the plastic limit (Stafford, 1979). There is an optimum moisture content at which tillage produces the maximum

number of large voids. This is equal to a gravimetric moisture content of approximately 0.9 of the soil's plastic limit (Ojeniyi and Dexter, 1979).

Compression results in increasing the bulk density. When tilling, the overall change may be a decrease in bulk density, yet the area below the tillage tool typically shows an increase in bulk density (Cooper, 1971).

Direct tension is not typically applied to soil by a tillage tool. However, failure in tension may be induced during soil manipulation (Gill and Vanden Berg, 1968).

Soil Recompaction. Subsequent to deep-tillage, certain events will reduce the pore space created by tillage operations. Several studies have been conducted on recompaction of deep-tilled soils located on areas undisturbed by mining. Larney and Fortune (1986) studied the effects of subsequent cultivation on a previously tilled area. Kouwenhoven (1986) studied the effects of natural events, such as rain, gravity and shrinkage on tilled areas. The problem of recompaction on a freshly tilled soil is due primarily to traffic that is necessary to prepare a seedbed.

The structure of a pre-tilled soil was found to affect its ability to recompact. When a dense, massive soil is deep-tilled it will break up into large clods, which will need to be further worked to prepare a desirable tilth for seed germination. Poorly structured or massive soils, such as one would find on a typical reclaimed minesite, are likely to need additional cultivation in order to prepare an adequate seedbed. While these massive soils have the greatest need for deep loosening, the additional cultivation passes required for clod breakup canceled the effects of deep tillage (Larney and Fortune, 1986).

Without traffic, some of the newly created macropores will collapse due to natural events such as rainfall, gravity and shrinkage (Kouwenhoven, 1985). A linear relationship exists between the amount of time after deep tillage and the amount of recompaction occurring naturally. Rainfall accounts for most of the naturally occurring recompaction. Gravity and shrinkage played only a minor role. In addition, natural recompaction was strongest on the coarsest soil. A silt loam soil experienced the least amount of recompaction by natural forces.

Blackwell et al. (1989) applied gypsum to vertical slots measuring 40.0 cm (15.7 in.) deep and 10.0 cm (3.9 in.) wide. The gypsum was deposited into the slot by gravity. This technique was found to increase crop yield by increasing infiltration and porosity, and provided protection from subsequent recompaction of the slot. The stronger, uncultivated soil adjacent to the slots supported the wheel load while maintaining the slot. This was contrasted to a surface application of gypsum followed by deep ripping. Recompaction was found to occur after one pass over the deep ripped zone and four passes over the slots. The injection of gypsum during deep ripping was not studied.

Recompaction of reclaimed mine soils has been documented as a byproduct of other investigations. In work conducted by Barnhisel (1986) there was a tendency for the bulk density to increase over a period of two years on ripped and nonripped areas. The density in both the ripped zone and below the ripped zone tended to increase. The cause of the increase was not investigated. Figure 2 shows a schematic of the stages of deep tillage as discussed above.

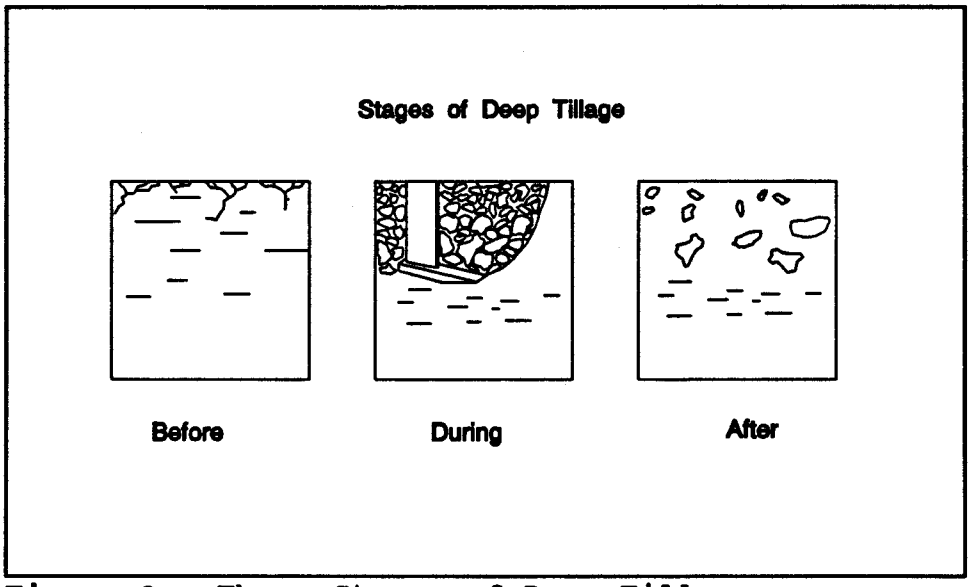


Figure 2 - Three Stages of Deep Tillage

Pressures Caused by Machinery. Pressures developed at the contact area between the soil and the machine depend upon the characteristics of both the machine and the soil. The distribution of pressure over the contact area is not uniform and depends on the characteristics of the tire or track and the soil. The pressure distributions within the soil, at a given depth below the surface, are a function of the amount of load, the size of contact area, the distribution of surface pressure within the contact area, the nature of the soil, soil moisture content, and soil bulk density. The magnitude of the stress decreases with increasing depth below the surface of the soil. An increase in load increases the depth of the stress bulb (Soehne, 1958).

An approximately equal pressure over the entire contact area can be assumed when a smooth-surfaced load is placed on a hard dry soil. This is not true for soft, moist soil. If there is plastic flow to the side of the contact area on a moist soil, then the pressure decreases toward the outside of the contact area and the pressure is more concentrated towards the center of the load (Soehne, 1958).

Typically, scrapers and dozers are used to move soil. Agricultural tractors are used to pull tillage tools through the soil. When a larger force is required to move the tool through the soil, a dozer may be used.

A summary of estimated ground pressures for various types of earthmoving equipment, which could be encountered in surface mine reclamation is given by Barnhisel (1988). Estimated scraper pressures range from 551 to 860 kPa (80 to 100 psi) for a pan capacity of 18.4 m^3 (24 yd^3). The range depends on the load of the scraper, either empty or full. Due to the rubber tires, the load is concentrated on a relatively small area. This leads to high contact pressures.

In the case of dozer tracks, the soil contact area is greater. Also, the dozer pushes the soil, instead of carrying it. This leads to lower total weights and lower average pressures. Typical dozer contact pressures range from 31.7 to 152.2 kPa (4.6 to 22.1 psi), depending on the type of dozer

(Barnhisel, 1988). Caterpillar, Inc. (1988) reports ground pressures of dozers (i.e., D7H, D8N, and D9N) ranging from 78.5 to 88.8 kPa (11.4 to 12.9 psi).

Estimated contact pressures for agricultural tractor tires are typically less than 137.7 kPa (20 psi) (Hillel, 1980). As equipment has increased in size and mass, machine designers have increased tire sizes to keep the soil surface pressure relatively constant. Taylor and Gill (1984) summarize the agricultural soil compaction problem. Pressures created by a standard agricultural tire were monitored in the subsoil at depths of 52 cm. (20.5 in.).

Methods of Measuring Soil Compaction. There are several available methods of measuring soil compaction. The three methods used in this study were bulk density, mechanical resistance and hydraulic conductivity. Background information on these methods is discussed here; however, their application to the project is described in Chapters III and IV. No single method is considered best for measurement of compactionin all cases.

Bulk Density. A common method used to measure compaction is the bulk density of the soil. Freitag (1971) reviewed methods of measuring bulk density. Wet bulk density is defined as total mass per unit volume and is expressed as g/cm^3 (lbs/ft^3). Due to varying moisture content, this is rarely reported. Dry bulk density is defined as the dry soil weight divided by wet volume and is expressed as g/cm^3 (lb/ft^3) and will be referred to as "bulk density" or "density". This value is typically reported in compaction studies. A low bulk density value corresponds to a less compact soil. As the bulk density increases, the soil particles come closer together. Smaller particles start to fill in the voids between the larger particles. Bulk density measurements may be taken gravimetrically or with a nuclear device.

Gravimetrically, bulk density is obtained by measuring the dry weight of the soil and its wet volume: Bulk Density = Dry Weight/ Wet Volume g/cm^3 (lbs/ft^3)

Several methods are available to measure the volume depending upon the soil characteristics. Core samples are best suited for soft to firm, cohesive or plastic soils. An accurate volume of brittle, rocky or cohesionless soils generally cannot be obtained with the core sampling method. Alternative techniques require the determination of the volume of the hole excavated in the soil by filling it with a free flowing material. The volume of the material is determined either by measuring the weight needed to fill the hole or by directly measuring the volume as it flows into the hole. Typical materials used are dry sand, water, and oil (Freitag, 1971).

Manufacturers of nuclear devices provide operational and scientific information for measuring bulk density (CPN Corporation, 1988). The nuclear device is referred to as "nuclear gage" or "gage" in this report. Radioactive methods measure in situ bulk density and utilize two forms of radiation: gamma and neutron. The unstable isotopes contained within the source will slowly decay to a more stable state. This act of decay produces emissions of energy as the atoms disintegrate. Two types of gages are available: single probe and dual probe. The dual probe nuclear gage contains two source isotopes in one probe (one emits gamma, one emits neutron radiation). The gamma radiation detector is located in the other probe, while the neutron radiation detector is located in the source probe. The single probe gage also contains two source isotopes, but both detectors are located at the base of the instrument, which remains on the soil surface. Due to the decay of the radioactive sources over time, new standards are established in order to calculate the soil count/standard count ratio, which is used in bulk density determinations (CPN Corporation, 1988).

For a dual probe gage with a noncollimated source, the gamma photons pass from the source to the detector in a somewhat arched path, which at the center may vary from 5.1 to 10.2 cm (2.0 to 4.0 in.) in thickness (Ayers and Bowen, 1985). This thickness is inversely related to the density of the soil. A dual probe gage measures the average density of a finite thickness. This causes errors when measuring sharply changing soil density profiles (de Vries, 1969). However, this is not a problem if the soil density profile gradually changes, or the average soil density at a specific depth is required (Ayers and Bowen, 1985). The effect of changing soil density profiles on the resolution of a noncollimated dual probe gage has been investigated (Ayers and Bowen, 1985; Vomicil, 1954; de Vries, 1969). The zone of interface influence was found to range from 5.1 to 10.2 cm (2.0 to 4.0 in.).

Mechanical Resistance. Soil strength is related to mechanical resistance and is defined as "the ability or capacity of a particular soil in a particular condition to resist or endure an applied force" (Gill and Vanden Berg, 1968).

Resistance to penetration depends upon soil properties such as texture, structure, mineralogical composition, moisture content and density. A coarse-grained soil will have a large average pore diameter and a low resistance to penetration. A soil with a well developed structure will contain macropores, which can be easily penetrated. Soils with a high moisture content have a lower resistance to penetration than a soil with a lower moisture content. Generally soils with a low bulk density have a lower resistance to penetration (Thompson, Jansen, and Hooks, 1987).

A common method used to measure the soil's resistance to penetration requires forcing a shaft with a cone-shaped tip into the soil. In addition to the above mentioned items, the mechanical resistance encountered also depends upon the interaction of the soil with the cone. This includes the cone's diameter and angle, material of composition and rate of advancement. Since there are many factors affecting the resistance to penetration, this index can be used only when all other factors are held constant (Vomocil, 1957).

There are two methods of advancing the cone penetrometer: impact and continuous-stress. Since the rate of advance affects the magnitude of the force required to cause penetration, the impact method proves to be less desirable (Freitag, 1971). The continuous-stress type is standardized with respect to cone dimensions and rate of advancement. Two sizes of cones are recommended, one for soft soil and one for hard soil. Both configurations are 30 degree right circular cones and are located at the base of a shaft (American Society of Agricultural Engineers, 1988). The resistance to penetration is recorded as a continuous function of depth with a chart recorder or with a computerized data acquisition device. Manual penetrometer readings may also be taken with a proving ring at pre-determined depth increments. The cone index is found by dividing the resistance by the cross-sectional area of the cone.

The mechanics of soil failure during penetration include shear failure, plastic flow, and compression. Direct interpretation of the penetrometer results in terms of the soil strength is currently unavailable. However, the penetration resistance is considered to be related to the strength of the soil and is termed penetrometer soil strength (Hillel, 1980).

Fluid Conductivity. Fluid conductivity of a soil is a measure of its ability to transmit a fluid. It is a function of the structure, texture, porosity (or density), pore-size distribution, moisture content, and characteristics of the permeating fluid (viscosity, density, chemical composition). Darcy's law was developed for a porous medium saturated with water. Since its development, it has been applied to unsaturated hydraulic and air conductivity.

Since the macropores conduct water at a faster rate than the more tortuous micropores, generally a soil with a lower density (more macropores) will conduct water faster than a more compact soil. However, this method of measuring compaction has not been widely used (Freitag, 1971).

Similitude. In this report, the concept of similar systems was considered to scale field tillage equipment for use in the laboratory. The relationship between the field system and the laboratory system model was determined since the same physical laws govern the behavior of both systems.

The similarity considerations were geometric (ripper dimensions), dynamic (ripper speed and acceleration) and kinematic (soil failure patterns). The kinematic similarity requirement depends upon the geometric and dynamic similarity (Wismer, Freitag, and Schafer, 1976).

Geometric Similitude. The Reynolds number is a well known dimensionless ratio that describes the phenomenon of laminar versus turbulent flow for liquids with various densities, viscosities and velocities flowing in pipes with various diameters (Mott, 1979). This ratio was developed by a technique used to analyze the dimensions of all pertinent variables involved in the system. Likewise, the operating- depth-to-the-cutting-width of the ripping tool and angle of the ripper foot off the horizontal (rake angle) are two dimensionless ratios that adequately describe the phenomenon of soil failure, all other variables (soil and operating conditions) remaining the same (Schafer, 1989). When the rake angle is measured in radians, the quantity is dimensionless.

Dynamic and Kinematic Similitude. Several studies have investigated the effect of ripper speed on soil failure patterns. To establish perspective, 50.0 cm/sec (19.7 in./sec) converts to 1.1 mph which is a typical field ripping speed.

Stafford (1979) investigated ripper speeds at various moisture contents. At very low speeds of 5.0 mm/sec (0.2 in./sec) soil failed in a manner similar to failure under field ripping speeds for a moisture content less than the plastic limit. That is, the angle of the slip line was found to be close to the theoretical value of 45 degrees minus $\theta/2$, where θ is the angle of internal friction of the soil. The soil failed as a rigid brittle material along a thin surface of maximum shear stress at regularly spaced intervals. The failure was described as crescent shaped. At very high ripping speeds, greater than 5 m/s (16 ft/sec), a change in failure occurred, from shear to plastic flow. This change occurred at a critical velocity known as the plastic propagation velocity. Therefore, soil reactions were found to be rate dependent at very high velocities. However, typical field and laboratory ripping speeds fall well below this upper limit.

Soil Failure Patterns. All other variables remaining constant, soil failure is determined by the ratio of the operating depth to the effective cutting width of the ripper (depth-to-width ratio) and the effective rake angle. The effective cutting width and effective rake angle corresponds to that part of the ripper that provides the major thrust to the soil. Generally, a ripper with a small depth-to-width ratio, develops crescent failure over the entire working depth, so that the slip line goes to the base of the ripper. As the depth-to-width ratio is increased, usually by increasing the operating depth, the crescent failure is limited to a region above a critical depth. Below this critical depth, the soil moves laterally. Any changes in soil characteristics (i.e., density, angle of internal friction and moisture content) as well as ripper configuration and operating variables will affect the critical depth (Godwin and Spoor, 1977). The rake angle has a similar effect of increasing or decreasing the depth of crescent failure. Generally, when the rake angle is decreased, the depth of crescent failure is increased (due to the downward migration of the base of the crescent failure along the

length of the ripper). These two parameters adequately describe tillage operations. There is a critical depth for all ripper shapes and configurations in a given soil condition.

Tillage Mathematical Models. Several models have been developed to predict the volume of failure caused by ripping and the forces acting upon the ripper. Payne and Tanner (1959) established basic principles of soil failure under various ripper configurations. McKyes (1977) investigated the case of crescent failure reaching the base of the ripper. Godwin and Spoor (1977) proposed a method for estimating the critical depth of soil failure when the crescent failure did not reach the full length of the operating depth.

Pneumatic Conveying. This section of the literature review pertains to design elements that are addressed in Chapter VI.

The purpose of a pneumatic conveyer is to move solids from one location to another. There are two basic classes of pneumatic conveyors: negative (vacuum) and positive pressure.

Generally, bulk solids are a mechanical mixture of grains of a solid of various sizes. Bulk solids consist of particles so small in comparison to the container that they are considered as a continuous mass.

The material used in pneumatic conveying must be at least air dry and free flowing. Generally, material that is friable and easily broken, such as straw, is not likely to be successful in pneumatic conveying, except at low pressures (Stoess, 1970).

The flow properties of granular material depends primarily upon the particle size, shape, and moisture content. Moisture affects the cohesion of particles and adhesion of the material to the container walls. Generally, cohesive materials are difficult to convey pneumatically since they do not fluidize well (i.e., not easily entrained in air).

The angle of repose (or angle of internal friction) depends upon the particle's composition and shape of the particles. The lower the angle, the more likely the material is to flow (Stepanoff, 1969).

Flow of material in air is affected by the physical properties of the material, the Reynolds number and the material-to-air ratio. Classification of material is made on its ability to flow. Pressure drops are due to the drag forces on the particle, acceleration of the particle and friction of the air (Wen, 1976).

The conveying of material through the air is broken into two main categories: dilute and dense phases. The amount of material and air flowing in the pipe determines the phase of transport. The ratio of material to air is conventionally used to describe the flow. However, a visual inspection of the flowing material is also used to determine the phase classification, as described below.

In the dilute phase, the conveyed material is distributed uniformly throughout the cross sectional area of the pipe. To achieve this, low material-to-air ratios must be maintained. The dilute phase allows for a stable transportation of material. The minimum velocity needed to carry the material without allowing them to settle out is termed the "saltation velocity" for horizontal transport and "choking velocity" for vertical transport (Wen, 1976).

In the dense phase, the material is concentrated in plugs or on the bottom of the horizontal pipe. This occurs as the material-to-air ratio is increased causing some particles to settle on the bottom of the pipe and drift along. Further increases in the ratio results in plugs of material pushed along by plugs of air. Even higher ratios cause the material to build up and become continuous in the pipe. The material on the surface will flow in the form of ripples with most of the material remaining stationary, much like a sand dune migrates. Flow of material at high ratios are typically unstable, with large fluctuations in pressures. Plugs of material cause high pressure drops as the plug is expelled (Wen, 1976).

Pressures are divided into three general categories:

low	< 103 kPa	(< 15 psi)
medium	103-310 kPa	(15-45 psi)
high	309-861 kPa	(45-125 psi)

Low pressure systems handle dry, crushed and fibrous material. Medium and high pressure systems handle competent solids (Stoess, 1970).

The type of system needed is first determined by the particle size and shape of the material to be conveyed. Tables of particle sizes and corresponding pressure ranges are available (Stoess, 1970). Generally, granular, solid material can be conveyed at any desired pressure range. Lumpy or irregularly shaped particles, such as sawdust and wood chips, can be conveyed only at low-pressures. After the type of system is determined, the necessary air requirements to transport the desired volume of material is determined. The basis for design of high pressure systems is actual experience in the handling of same or similar materials (Stoess,1970).

A variety of equipment is available to convey material pneumatically. Components of positive pressure systems are discussed by Stoess (1970).

Solids Pumps. Several types of solids pumps are available and are used in the low and medium pressure range. Fuller-Kinyon Pumps are used with fine grained material (50-200 mesh). The maximum air pressure is 310 kPa (45 psi). The material to be conveyed enters the hopper and is advanced by gravity to the impeller screw, which rests horizontally. The material is then metered into a mixing chamber. A modification of this pump uses a lower air pressure of 83 kPa (12 psi).

Blow Tanks. A blow tank is a container filled with material that is funneled into a pipeline by gravity and the energy of expanding compressed air. Blow tanks are categorized as a universal pressure system, since they are designed to operate under low, medium or high pressures. If the material in the blow tank is to be fluidized, the tank is first filled with material to a pre-determined level. Air is introduced into the tank at or near the discharge outlet. As the air permeates the material, the tank pressure forces the material out of the tank. The volume flow rate of the material is controlled by a valve located at the discharge point of the tank and by the air pressure applied. Blow tanks typically use a low ratio of material-to-air in order to maintain a dilute phase transport. The size and shape of the outlet must be designed for gravity flow, which is typically confined to the middle portion of the container. The angle of repose of the material should be less than the inclination of the funnel base. The terms "arching", "bridging", and "doming" are used to describe the stoppages of flow from material storage tanks. The free surface of the blocked material forms an arch, a bridge, or a dome. Moisture in the material can be a cause of the blockage (Stepanoff, 1969).

Metering Devices. The objective of the metering devices is to distribute the material uniformly into the air stream. Several metering devices are available and are discussed by Wen (1976). The rotary air-lock or "star wheel" feeder is the most frequently used device to feed solids uniformly. It can be used for negative or positive pressures. This device consists of an axis mounted horizontally with a paddle wheel or star wheel attached. The tips of the vanes make an air tight lock with the housing of the feeding unit (clearance of .013 cm (.005 in.)). The incoming material fills the top section of the wheel. As the wheel rotates, the material exits at the bottom position where the material is dropped by gravity into the air flow. By varying the rotation rate of the wheel, the flow rate of the material can be controlled.

Mechanical vibrators are used to maintain the flow of material. Vibrations in the horizontal plane are more effective than vibration in the vertical plane. The vibrator is attached to the outside of the tank.

Pipelines and Hoses. The conveyor lines must be designed so that flow is not restricted. Restriction of flow would cause the material to settle and stop moving, causing a blockage of flow. The pipe or hose should be as straight as possible, with as few direction changes as can physically be allowed. Any changes of direction should be made with long-radius bends. The bend-radius should be 6-12 times the pipe diameter. Pipe fittings should be flush with as few abrupt changes in inside diameter as possible. Valves are often the location of plugging. If irregularly sized material is fed into the system, it may first need to be reduced in size with a chopping device. The flow rate of the solids can be measured with an instrument that focuses a beam of light into the stream. The blockage of the light beam is used to determine the flow rate (Wen, 1976).

Fluidized Beds. A fluidized bed is a layer of solid particles with a stream of air passing upward through the particles at a velocity that sets them in motion. The range of fluidizing conditions varies from smooth to bubbling to slugging. Smooth fluidization requires minimum air velocity. The bed of particles will expand, but will remain intact. As the velocity increases, air bubbles develop and move through the expanded bed. The particles are violently agitated due to the rising bubbles. Even greater velocities will lead to the pneumatic transport of the particles. The range of velocities that allow for the transport of material is termed the slugging range (Wen, 1976).

Tillage Experiments Conducted with Air Pressure. There have been a variety of experiments done with air injection with respect to deep tillage equipment.

The use of an air film between the soil and a tillage tool was investigated by Bigsby (1961). A flat perforated surface through which air could be forced was constructed. This instrument was not successful in reducing the draft force. The draft force is defined as the resisting force that the soil exerts on the tillage tool.

In another experiment, a chisel type tillage tool was used with a series of orifices in order to reduce the draft force (Mink, Carter, and Mayeux 1964). This experiment succeeded in reducing the draft force required for tillage operations.

Fomin (1970) developed equations to calculate the distribution of air pressure to be applied at various sections of a moldboard plow in order to provide adequate lubrication.

Araya (1984, 1985) used a chisel-type tillage tool with air pressure to reduce successfully draft force, develop cracks in the soil in order to drain fields, and to dispose of sewage sludge. The nozzle was located at the leading tip of the foot and directed upward.

Another series of studies were conducted with the concept of blowing mulch into the channel created when tilling (Watson and Phillips, 1962; Hyde, et al., 1986). Crop residue was blown directly into the slot and mechanically compressed. The depths of tillage ranged from 20-61 cm (8-24 in.). The primary benefits of this method were that it controlled erosion, improved infiltration, provided for disposal of excess crop residue, and produced higher yields.

Studies involving air injection methods to reduce soil compaction were not found. The potential for compaction reduction exists in Araya's work, since cracks were created in order to drain paddy fields.

Hydraulic Fracturing. Fracturing and material injection of reservoir rocks are practiced in the oil and gas industries. Fracturing was accomplished by pumping a high-viscosity slurry (gel, emulsion, or foam) and granular material into a well. When the applied pressure exceeded the rocks' tensile and compressive stresses, fractures were formed. The fractures opened at high hydraulic pressure are kept open by support of pressure-resistant proppants, which are injected into the crack and inhibit its closure (Mader, 1989). The fractures were found to lose its fluid carrying capacity unless it was propped with granular material (Howard and Fast, 1970).

The first hydraulic fracturing jobs used natural quartz sand. Crushing of the sand limited its application. A variety of materials were tried in subsequent years, such as glass and plastic beads, metal shots, and ground walnut shells. Crushing of the glass beads and walnut shells limited their application. However, these materials were used, depending on the job site, before the invention of synthetic ceramic proppants. Since 1976, the industries have used sintered bauxite. This material resists high closure stresses (Mader, 1989).

CHAPTER II

FIELD OBSERVATIONS

Field experiments were conducted to determine the potential of various measures for long-term amelioration of excessive compaction of prime farmland soil during reconstruction. The specific objectives of the field study were:

1. To determine the comparative effects of different species of vegetation, planted immediately following reconstruction, on amelioration of excessive subsoil compaction.
2. To determine the effect of deep tillage or ripping on reduction of subsoil bulk density.
3. To determine the effect of placement method on initial subsoil bulk density and on changes in bulk density over time.

Experimental Methods

Experimental plots were reconstructed using prime farmland soils at the River Queen and the Gibraltar surface mines of the Peabody Coal Company in northern Muhlenberg County, Kentucky.

River Queen Plots. A Sadler (Glossic, Fragiudalf, fine-silty, mixed, mesic) silt loam soil was reconstructed at the River Queen site using scrapers and dozers. A mixed fine-silty subsoil (B horizon) material was deposited over graded spoil to an approximate depth of 800 mm (32 in.) in successive layers deposited by scrapers. Approximately 200 mm (8 in.) of low organic matter silt loam topsoil (A horizon) material was then deposited by scrapers and graded by wide-track dozers to minimize ground contact pressure.

A rectangular area 91 m x 145 m (300 ft x 475 ft) of reconstructed soil was established at the site (see Fig. 3a). The area was divided into 16 plots, 7.6 m (25 ft) wide oriented N-S, separated by 1.5 m (5 ft) horizontal strips. Initial deep tillage treatments were then applied using a Rome ripper with parabolic shanks spaced 1.2 m (4 ft) apart to an approximate depth of 610 mm (24 in.). Soil was ripped following reconstruction at three levels of moisture content: dry, 1/2 field capacity and field capacity, with a non-ripped control. Each set of ripping treatments was replicated four times.

Various species of vegetation were superimposed on these experimental plots by subdividing the area in the E-W direction. Parallel strips or plots were established as follows from north to south (see Fig. 3a): 15.2 m (50 ft), local black locust; 15.2 m (50 ft), alfalfa (Vernal variety); 9.1 m (30 ft), KY 31 tall fescue; 21.3 m (70 ft), no-till soybeans; 9.1 m (30 ft), KY 31 tall fescue; and 21.3 m (70 ft), no-till corn.

During 1985 the corn and soybean plots were disked and planted and two-thirds of each plot was ripped in the E-W direction. In 1986, the plots were disked and planted, then 1/3 of each plot was again ripped in the E-W direction. The plots planted in black locust, alfalfa and fescue were mowed in 1985 and 1986. In 1987, the black locust plot was disked to a depth of 150 mm (6 in.) and the alfalfa and tall fescue plots were treated with herbicide. Subareas of each plot were again ripped and the entire area was planted to no-till corn. During 1988-90 the area was planted in no-till corn,

conventional corn and grain sorghum, respectively, with no additional ripping. Additional details concerning the experimentation associated with these plots is given by Powell et al. (1985).

Cylindrical soil cores (50 mm (2 in.) dia., 150 mm (6 in.) long) were collected from each ripping x crop plot area immediately after soil reconstruction (prior to any planting or ripping) in early 1984 using a Giddings hydraulic sampler. Initial bulk density was thus determined for each 150 mm (6 in.) layer of reconstructed soil. Additional core samples were collected in 1985 and 1986 in the corn plots and in 1987 in the alfalfa plots. In 1988 volumetric cores were collected and bulk density was also determined using a gamma ray attenuation gauge. The plots sampled in 1988 were: corn, never ripped; corn, initially ripped dry (N-S), cross-ripped (E-W) in 1985, 86 and 87; alfalfa, never ripped; and, black locust, never ripped. The corn and alfalfa plots were again sampled or measured in the fall of 1990 using a dual probe gamma density gauge.

Gibraltar Plots. Two prime farmland soils were reconstructed at the Gibraltar mine site. In addition to the previously-described Sadler soil, a Belknap (Aeric, Flavaquent, coarse-silty, mixed, acid, mesic) silt loam soil was reconstructed at this site. Table IA shows the horizon designations and depths for these two soils.

Two methods were used to reconstruct the soils in the fall of 1982. Eight parallel strips, 21.3 m x 97.5 m (70 ft x 320 ft) were deposited of each soil using two types of equipment handling and using both direct placement and stockpiling (see Fig. 3b). In the conventional method, 18.3 m^3 (24 cu. yd.) scrapers were used to deposit subsoil in successive layers or lifts of approximately 400 mm as needed. Grading was accomplished by dozers equipped with wide tread to reduce contact pressure. Approximately 200 mm (8 in.) of topsoil was deposited via scrapers and graded.

The other method involved the use of 32 m^3 (35 yd^3) end-dump trucks. The trucks deposited subsoil by horizon without driving on the plots. Grading of each horizon was done using wide track dozers. Topsoil was placed in identical fashion with final grading by dozers.

In the spring of 1983, alfalfa was planted at both ends of the area in 12.2 m (40 ft) strips, perpendicular to the main treatment plots. In the center, 12-row strips of corn and soybeans were alternated giving four replications. In the fall of 1984, one half of each main treatment strip was ripped to a depth of 610 mm (24 in.) in the areas planted in corn and soybeans. Only corn was planted in the interior subplots in 1984 and 1985. In 1986, the entire area was planted in corn, including the end strips which had been in alfalfa for 4 years. During 1987-90, the entire area was planted in corn, soybean, wheat and wheat, respectively. Additional details concerning the experiment plot design at this is given by Barnhisel et al. (1986).

A Giddings hydraulic sampler was used to extract volumetric bulk density cores from each of the soils prior to disturbance. Four replicated samples of 50.8 mm (2 in.) dia. x 152 mm (6 in.) cores were collected at depths of 0-152, 152-305, 457-610, and 762-914 mm (0-6, 6-12, 18-24 and 30-36 in.). Following construction of the plots, four replicated core samples were collected from each treatment strip at 152 mm (6 in.) depth increments to a depth of 914 mm (36 in.).

A dual probe gamma density gauge was also used to measure in situ soil bulk density. In 1989, four replicated measurements were made in interior zone of the following treatment strips for both soil types: a) direct scraper placement, never ripped; and, b) direct truck placement, never ripped. The measurement depths were 203 mm (8 in.), 508 mm (20 in.) and 610 mm (24 in.). In 1990, gamma density measurements were replicated 4 times for both soil types in the following treatment strips: a) direct scraper placement, never ripped; b) direct scraper placement, ripped; c)

direct truck placement, never ripped; and, d) direct truck placement, ripped. Measurements were made at 51 mm (2 in.) depth increments to a depth of 914 mm (36 in.).

Soil moisture content was determined at each bulk density sampling location. When volumetric cores were used to determine soil bulk density (prior to 1989), soil moisture content was determined gravimetrically. In 1989, small samples were collected during the drilling of vertical access holes for the gamma density gauge. In 1990, soil moisture content was determined using a gauge which measured neutron scattering. This method has been shown reliable for measurement, below a depth of approximately 100 mm (Black et al., 1965).

Results and Discussion

River Queen Plots. Figures 3c and 3d present the results of the various determinations of soil bulk density versus depth at this site. Dry bulk density is plotted versus depth for each major treatment examined. Thus, each plot represents the mean of four replicated measurements.

Comparison of bulk density versus depth profiles immediately after reconstruction indicates substantial compaction of subsoils when compared to this soil in its pre-disturbed state. Subsoil bulk density for the natural Sadler soil increase from approximately 1.43 Mg/m^3 at z = 230 mm (9 in.) to 1.63 Mg/m^3 at z = 838 mm (33 in.) (Powell et al., 1985). Subsoil bulk density following reconstruction was approximately 1.8 Mg\m^3 for all plots below the depth of 380 mm (15 in.), except for the non-ripped plots planted in corn, which was approximately 1.7 Mg/m^3.

The corn plots which were never ripped exhibited gradual increase in subsoil density from reconstruction until 1988, followed by a notable decrease between 1988 and 1990. Only in 1988 was subsoil density as high as that in the corn plots which received the most ripping. In these plots, the clear effect of the ripping treatments, as well as other factors operating over time, was to substantially decrease bulk density in the upper subsoil (400-600 mm), while having less effect on the deep subsoil (> 700 mm).

The alfalfa (non-ripped) plots exhibited a slight reduction in subsoil bulk density (500-700 mm) between soil reconstruction and 1988. In the upper subsoil (200-400 mm), bulk density tended to increase over time. On the other hand, the black locust (non-ripped) plots exhibited little change in upper subsoil bulk density, while indicating a modest increase in lower subsoil density.

Comparing the profiles among all plots in 1988 would indicate that ripping resulted in a clear reduction in upper subsoil bulk density, while perhaps increasing density of the lower subsoil (below depth of ripping).

Gibraltar Plots. Figures 3e and 3f present the results of the various bulk density versus depth profiles measured at this site. The bulk density immediately after reconstruction was substantially greater than in the pre-mined state at all depths for both soil types and placement methods. Further, there is no clear indication, in either soil type, that placement method significantly affected bulk density immediately after reconstruction. This was somewhat surprising since only dozer traffic was applied to the plots constructed by truck placement. The results would indicate that for these soils and the conditions which prevailed at the time of placement, dozer traffic compacted subsoil as much as scraper/dozer traffic.

Bulk density measurements taken in 1988 in non-ripped plots indicate that subsoil bulk density increased for $z \geq 500$ mm (20 in.) and decreased for z > 500 mm. The exception to this was

the truck-placed Belknap soil, where subsoil bulk density decreased at all depths, compared with the initial (1984) profile.

The 1990 measurements present contrasting behavior in the two soil types. In the Sadler soil, subsoil bulk density apparently decreased relative to the 1983 and 1989 measurements in both ripped and non-ripped plots. In the Belknap soil, however, subsoil density increased in the non-ripped plots compared to earlier measurements.

Table 1B presents a comparison of mean bulk densities measured in 1990 for the various experimental treatments, i.e. placement method and ripping, using Duncan's New Multiple Range Test (SAS, 1986). In the Sadler soil, ripping resulted in significantly lower bulk density (5% level) at the 610-762 mm (24-30 in.) depth in the truck-placed plots, whereas there was no significant reduction at any depth in scraper-placed plots. In the Belknap soil, ripping produced significantly lower bulk density within all subsoil depths except 610-762 mm (24-30 in.) in the truck-placed plots, while reducing density only in the upper subsoil (305-610 mm (6-18 in.)) in scraper-placed plots. Significantly lower bulk density for truck placement was indicated only in the Belknap soil at the 762-914 mm (30-36 in.) depth in plots which were ripped.

Table 1A. Horizon designation and depths of Sadler and Belknap soils (from Barnhisel et al., 1986)

Soil Series	Horizon	Depth from Surface (mm)
Sadler	Ap	0-180
Sadler	B2t, A'2	180-640
Sadler	Bx (fragipan)	640-1000
Belknap	Ap	0-200
Belknap	B21, B22g, B23g	200-900

Table 1B. The Effect of Placement Method and Deep Tillage on Subsoil Bulk Densities of Two Reconstructed Prime Farmland Soils by Duncan's New Multiple Range Test

Sadler Silt Loam

Depth (mm)	Truck Placement Not Ripped	Truck Placement Ripped (610 mm)	Scraper Placement Not Ripped	Scraper Placement Ripped (610 mm)
305-457	1.56[a]	1.45[a]	1.56[a]	1.55[a]
457-610	1.57[a]	1.49[a]	1.55[a]	1.54[a]
610-762	1.63[a]	1.49[a]	1.55[ab]	1.52[ab]
762-914	--	1.55[a]	1.56[a]	1.57[a]

Belknap Silt Loam

Depth (mm)	Truck Placement Not Ripped	Truck Placement Ripped (610 mm)	Scraper Placement Not Ripped	Scraper Placement Ripped (610 mm)
305-457	1.72[a]	1.55[b]	1.72[a]	1.59[b]
457-610	1.72[ab]	1.56[c]	1.78[a]	1.63[bc]
610-762	1.68[ab]	1.63[b]	1.76[a]	1.72[ab]
762-914	1.77[a]	1.63[b]	1.83[a]	1.79[a]

*At a given depth, mean bulk densities designated by the same letter are not different at the 5% level of significance.

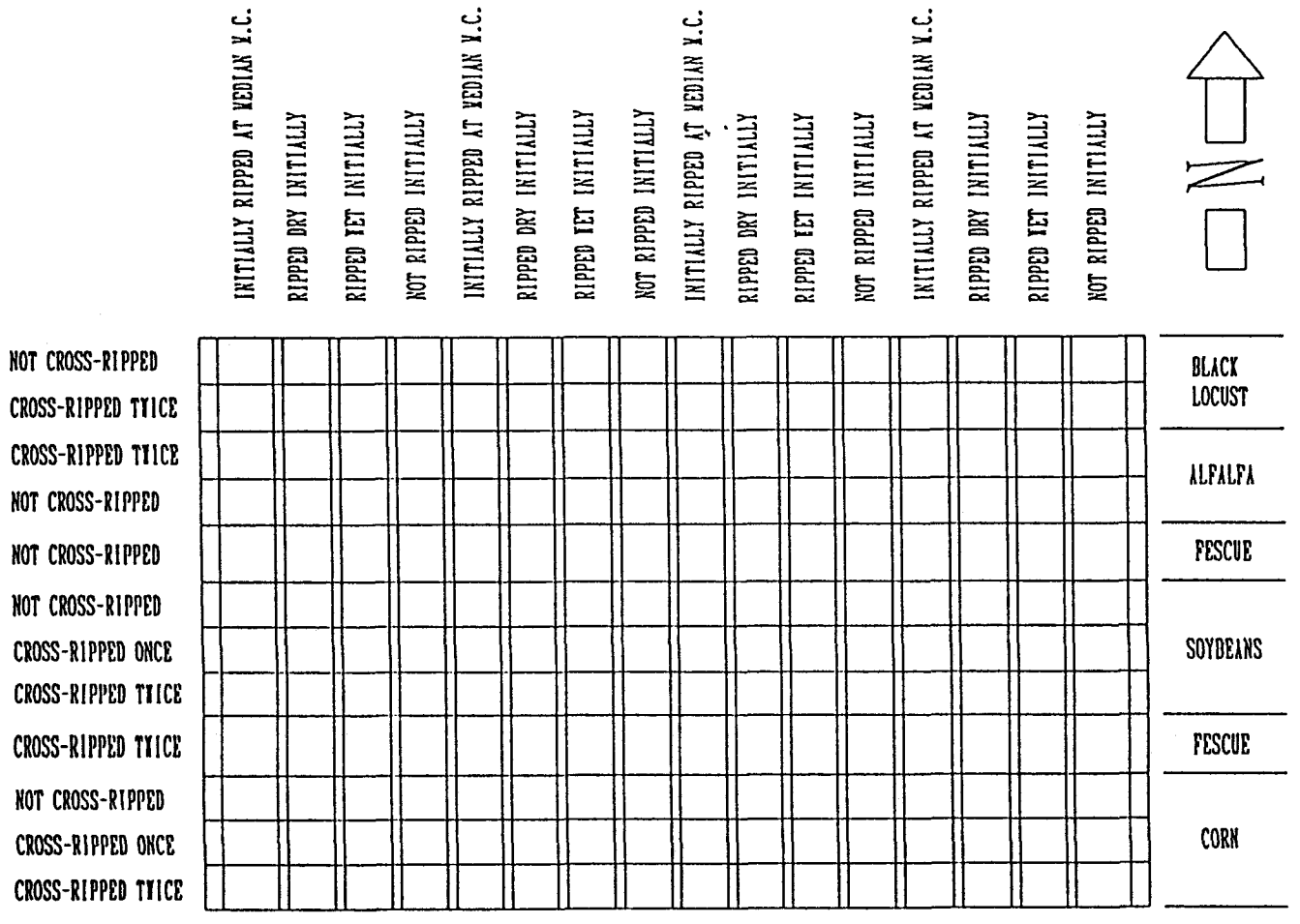


Figure 3a. Diagram of Experimental Reconstructed Prime Farmland (Sadler Silt Loam) Soil at River Queen Mine Showing Vegetative and Ripping Treatments.

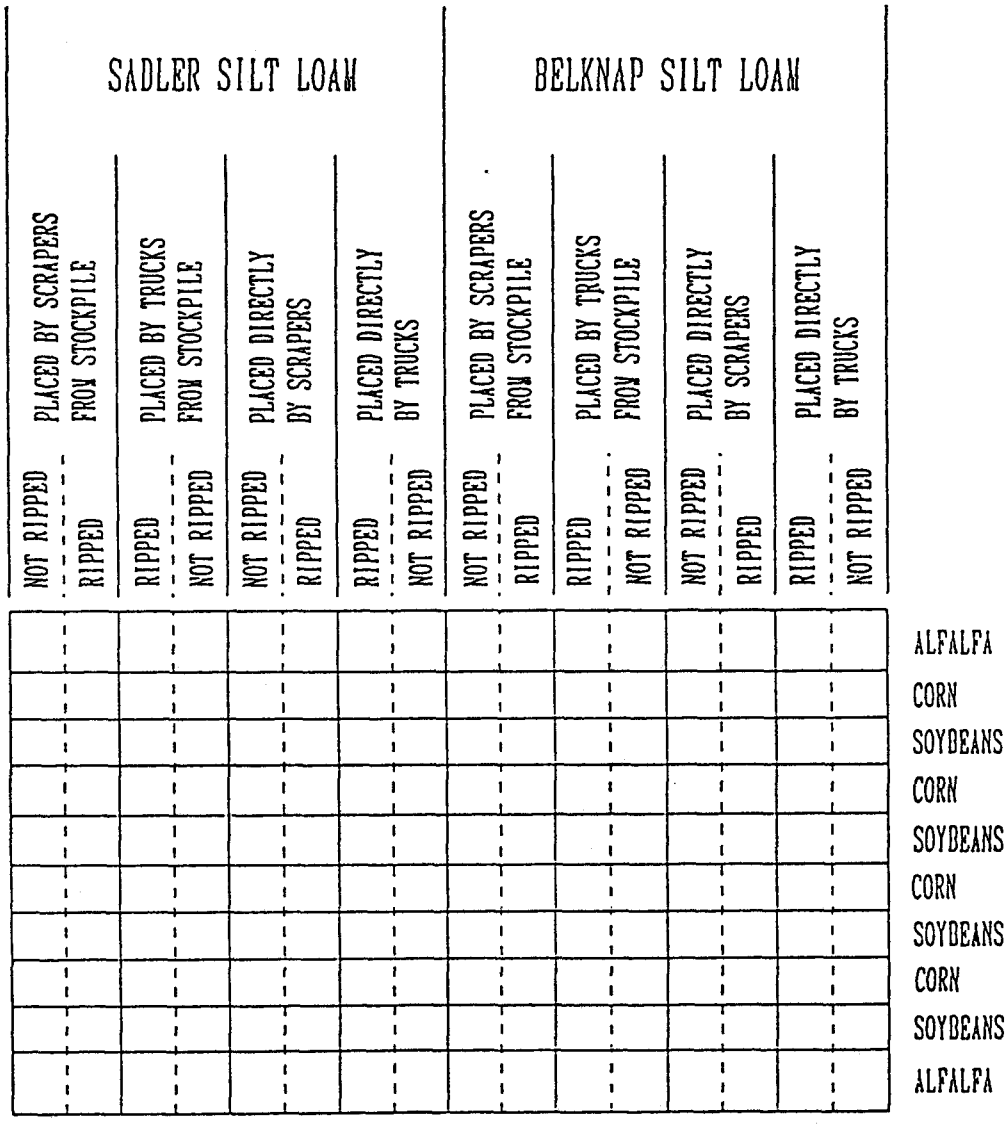
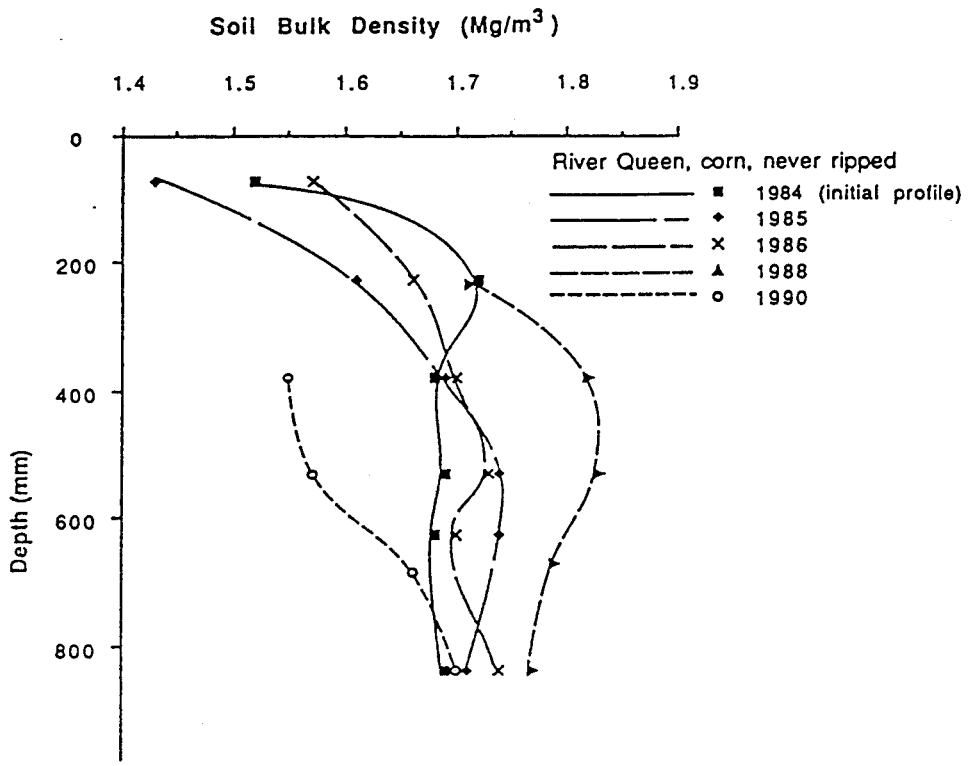


Figure 3b Diagram of Experimental Reconstructed Prime Farmland (Sadler and Belknap Silt Loam) Soils at the Gibraltar Mine Showing Placement and Ripping Treatments.



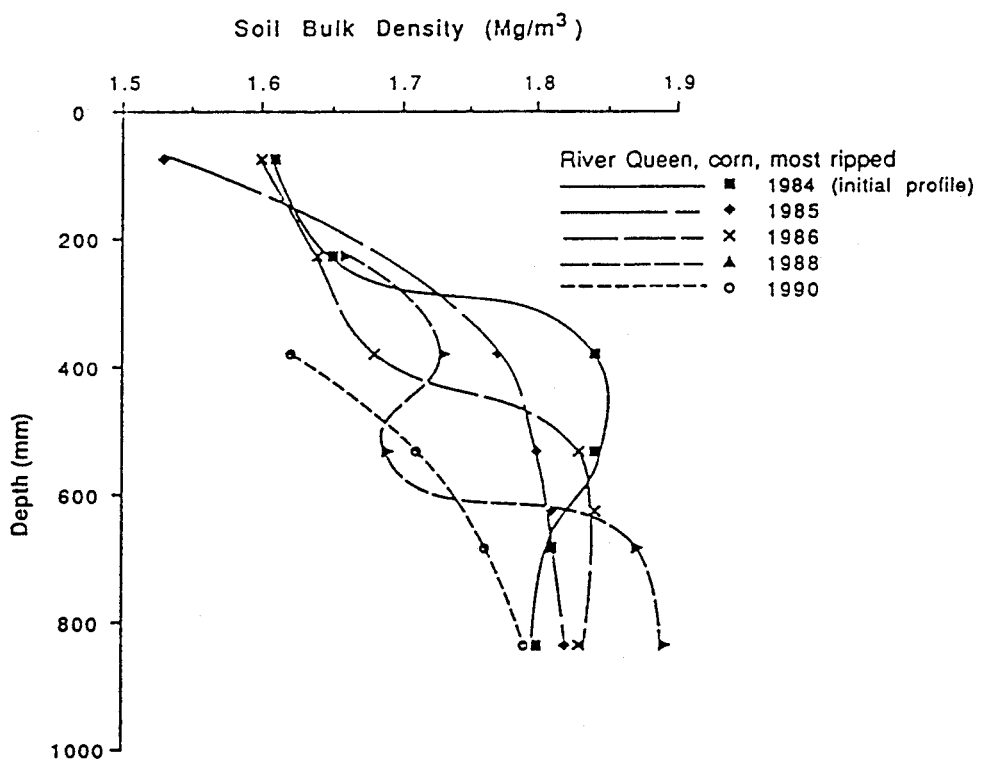
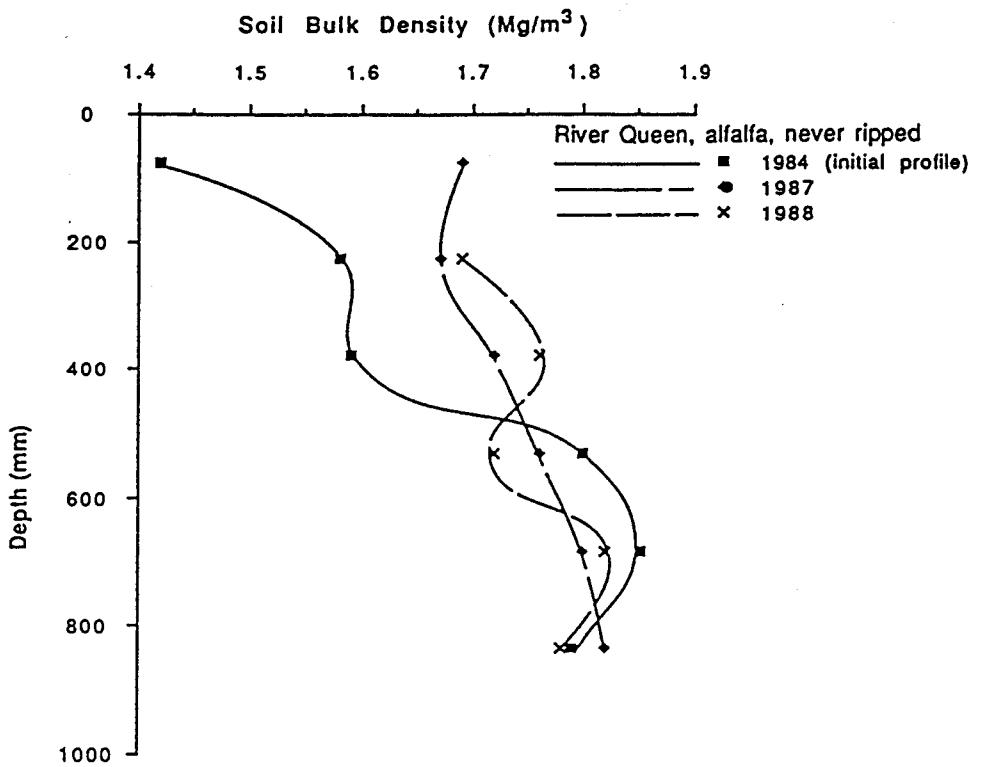


Figure 3c. Soil bulk density profiles at various times in experimental plots, initially planted in corn, at the River Queen mine.



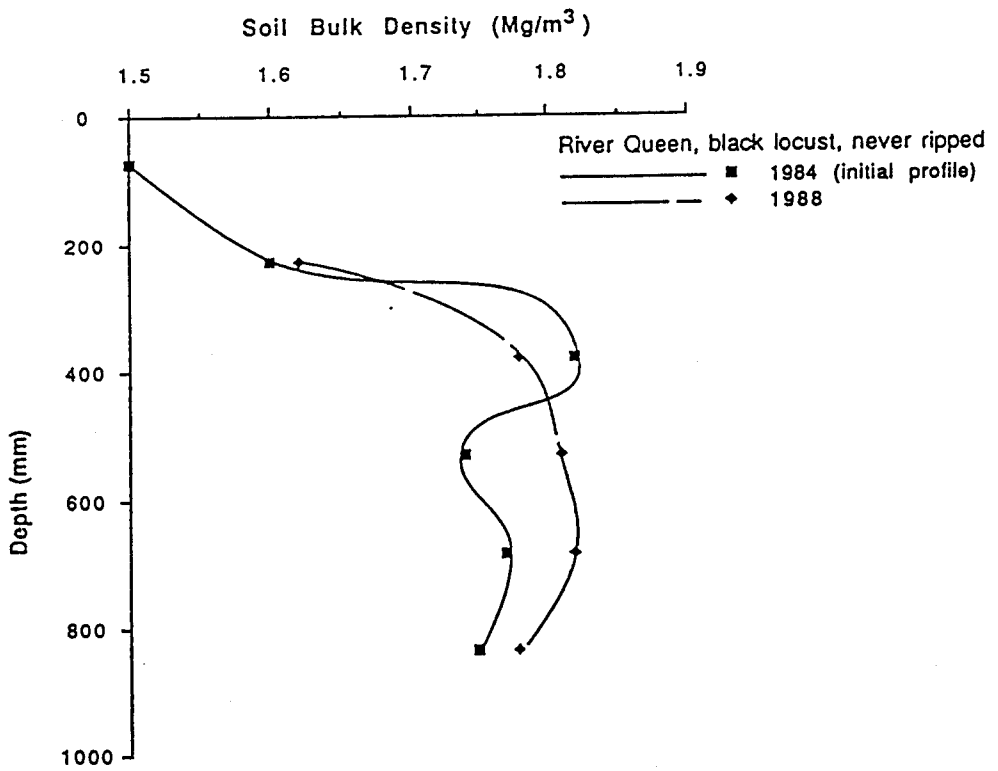
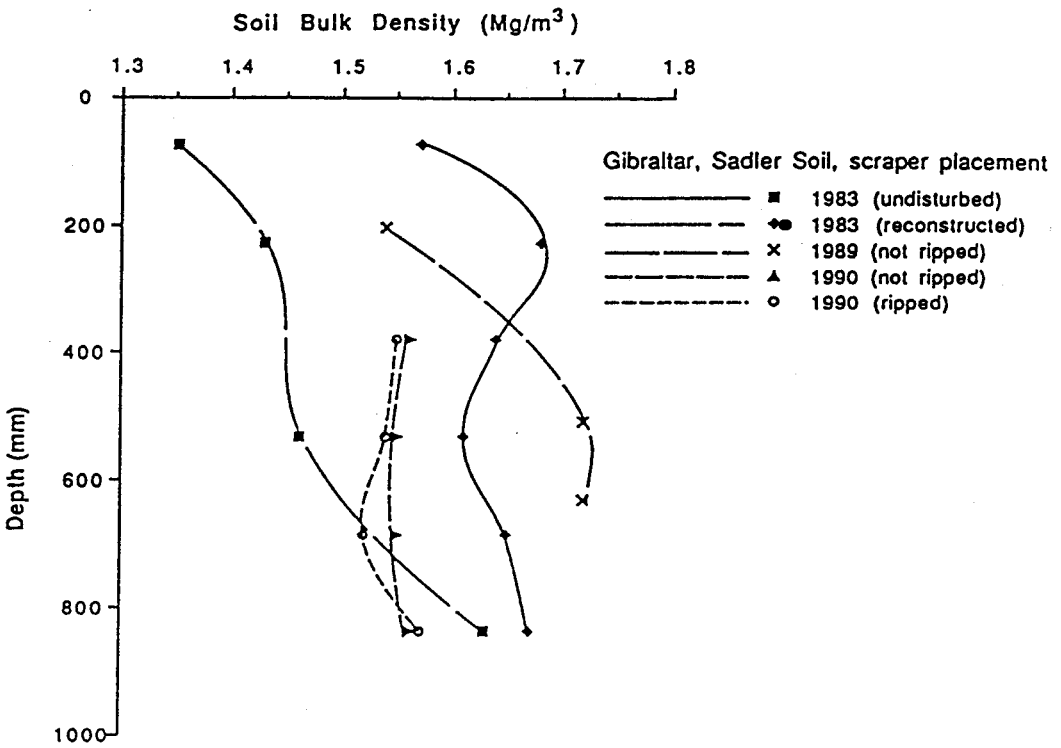


Figure 3d. Soil bulk density profiles at various times in experimental plots, initially planted in alfalfa and black locust, at the River Queen mine.



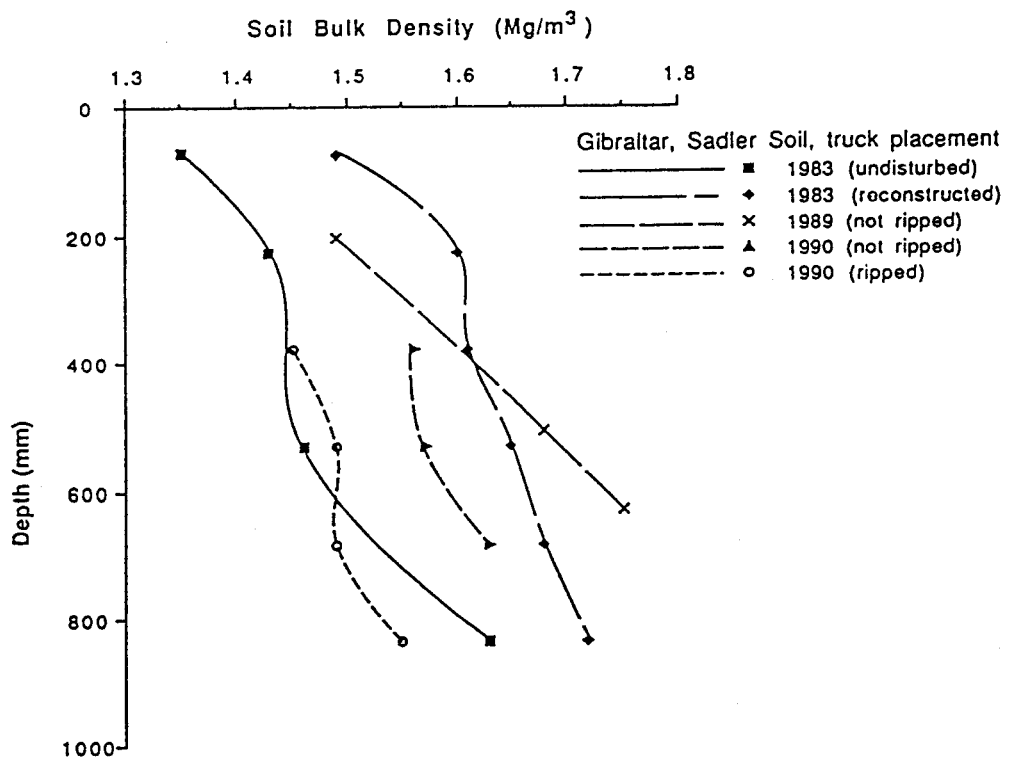
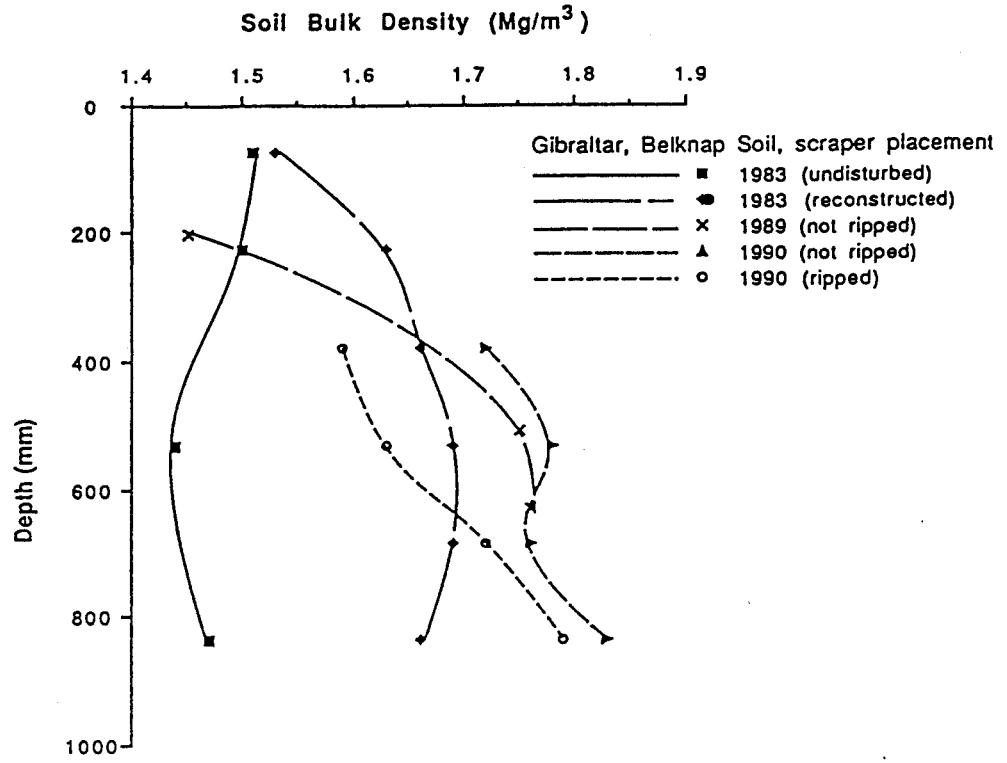


Figure 3e. Soil bulk density profiles at various times in experimental plots, reconstructed by two methods, in Sadler silt loam soil at the Gibraltar mine.



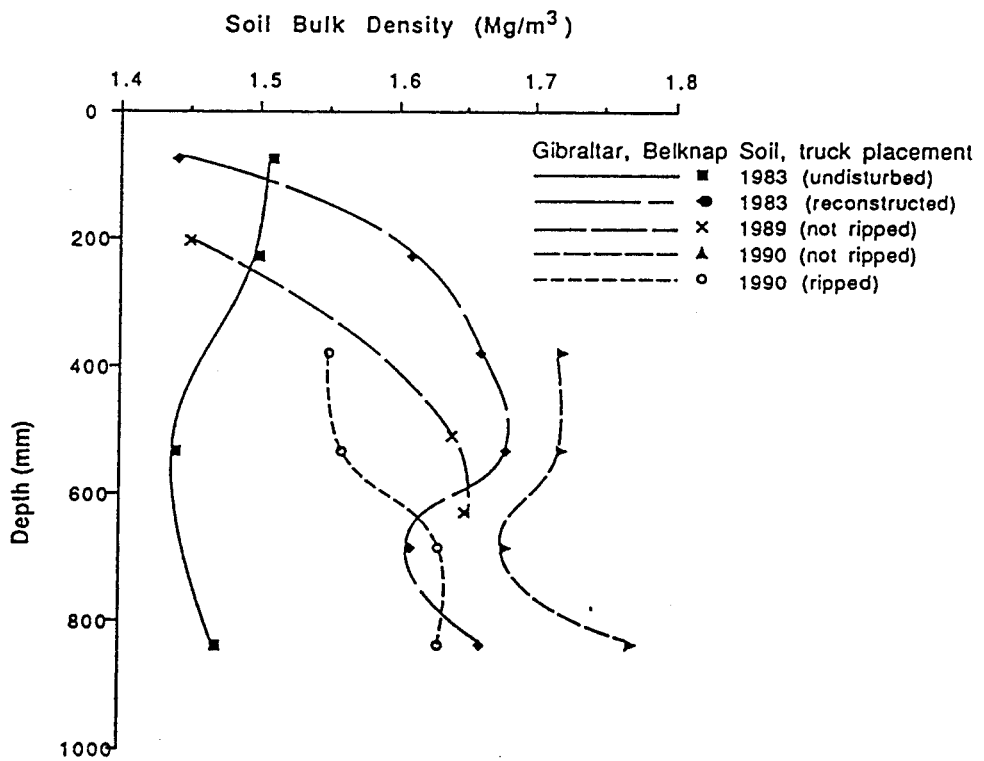


Figure 3f. Soil bulk density profiles at various times in experimental plots, reconstructed by two methods, in Belknap silt loam soil at the Gibraltar mine.

CHAPTER III

DEVELOPMENT OF THE LABORATORY MODEL

Belknap silt loam subsoil is a prime farmland subsoil as identified by the Soil Conservation Service (1983). This soil type has been affected by surface mining in western Kentucky and was selected for the deep tillage model. The first 30.5 cm (12.0 in.) of topsoil was removed with a backhoe. The depth of subsoil excavation below the surface ranged from approximately 30.5 to 121.9 cm (12.0 to 48 in.). Approximately 3.8 m^3 (5.0 yd^3) of subsoil was deposited into an end-dump truck with a backhoe. Upon arrival at the laboratory, the soil was removed from the truck with hand shovels and transported with wheel barrows. The removal and transportation of the soil from the truck to the laboratory facilitated mixing of the soil profile.

This soil type was probably formed from the weathering of local sandstones, shales, and siltstones of the Upper Pennsylvanian Lisman Formation. The soil was collected on an open pasture area near a perennial tributary of the Green River (Thorofare Branch). The surrounding area is a rural farming community. Generally, the flood plain areas of the Green River are cropped. However, small tracts on the ridgetops are also farmed. The cleared prime farmland is currently being used as pastureland and may be occasionally cropped for hay. These prime farmland soils are not currently being cropped on a yearly basis.

Soil Information

The Belknap series is a deep, poorly draining soil formed in acid alluvium. Belknap is geographically associated with Vicksburg, Collins, and Waverly soils. The soil profile is described as follows (Soil Conservation Service, 1983):

- 0-20.3 cm (0-8.0 in.); silt loam; weak, fine granular structure; very friable; many roots.
- 20.3-30.5 cm (8.0-12.0 in.); silt loam; distinct light, gray mottles; weak, subangular blocky structure; very friable; strongly acid.
- 30.5-50.8 cm (12.0-20.0 in.); light, brownish-gray silt loam; faint, brown mottles; medium to coarse subangular blocky structure; very friable, strongly acid.
- 50.8-91.4 cm (20.0-36.0 in.); gray silt loam; pale-brown and yellowish-brown mottles; coarse, subangular blocky structure; very friable; strongly acid.
- 91.4-121.9 cm (36.0-48.0 in.); gray silt loam; dark- grayish brown mottles; weak, coarse, subangluar blocky structure; very friable; few black concretionary stains; strongly acid.

The color of the soil gradually changed from the initial excavation color of drab mottled grays, yellows and browns to the laboratory color of pale yellows and browns with orange and gray mottling. The excavation colors are an indication of a poorly drained soil. The laboratory colors indicate good aeration and oxidizing conditions. The bulk density of undisturbed Belknap subsoil is reported by the Soil Conservation Service (1991) to range from 1.25 to 1.50 g/cm^3. A range of 1.44 to 1.51 g/cm^3 is reported by Barnhisel (1986).

Proctor Compaction Test. The moisture-density relation of the soil was found (Commonwealth of Kentucky, 1979). A weight of 2.5 kg (5.5 lbs) was dropped from a height of 30.5 cm (12.0 in.) into a mold measuring 10.2 cm (4.0 in.) in diameter and 11.7 cm (4.6 in.) deep. The optimum mass moisture content for compaction purposes, for a standard compactive effort, was found to be

approximately 19.0 % and the maximum dry density was found to be approximately 1.72 g/cm³. See Figure 4 and Table 2. Similar results were reported for the same soil type (Ali, 1991).

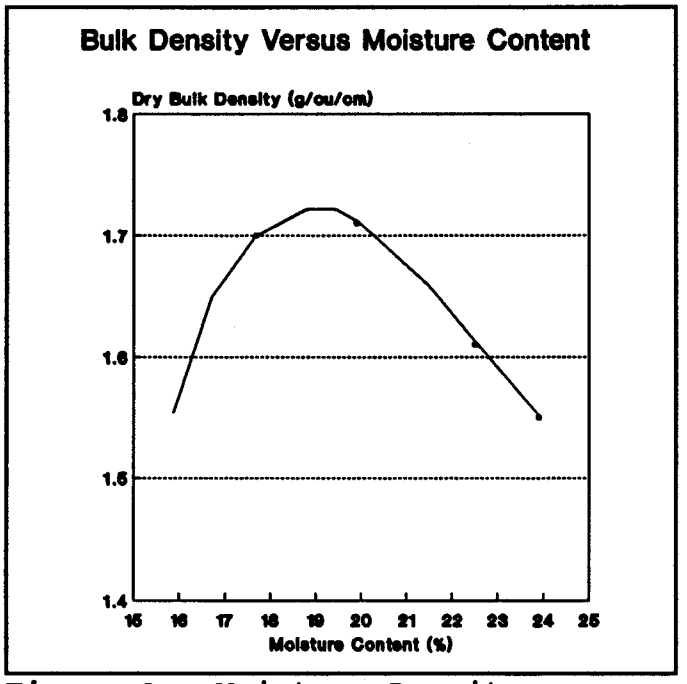


Figure 3 - Moisture Density Relationship

Table 2
Moisture Density Relationship

Density (g/cm³)	1.70	1.71	1.61	1.55
Moisture Content (%)	17.7	19.9	22.5	23.9

Particle Size Analysis. A particle size analysis was conducted by the Agronomy Department at the University of Kentucky. The standard used was developed by the United States Department of Agriculture, Soil Conservation Service (Soil Conservation Service, 1984). The model soil showed a particle size of 63.8 % silt, 23.4 % clay, and 12.8 % sand. Over half of the particles are of the size called "silt." This distribution of particle sizes defines the model soil as a silt loam. When dry it may appear cloddy, but the clumps can be readily broken, and when pulverized it feels soft and floury. When wet the soil readily runs together and puddles. (This description applies only to the silt loam in the undisturbed state.) Published particle size analysis for a Belknap silt loam, or similar soil, have not been located.

Clay Mineralogy. The mineral constituents of the model soil were determined by the Kentucky Geological Survey with the method of X-ray diffraction. The clay sized particles (< .002 mm) were prepared for mineralogical analysis according to the procedures described by Jackson (1964). The phenomenon of X-ray diffraction involves the scattering of X-rays by atoms of a crystalline mineral.

Since no two minerals have exactly the same interatomic distances in three dimensions, the angles at which diffraction occurs is unique for each mineral. The identified minerals were vermiculite, montmorillonite, illite, kaolinite, and quartz.

The kaolinite exhibits less plasticity, cohesion and swelling than most other clay minerals. The vermiculite and montmorillonite are expanding types of clay minerals. Because of this, the clay will exhibit swelling-shrinkage behavior, cracking, crusting, and have a high plasticity and cohesion. When drying, montmorillontic soils tend to form unusually hard clods. Illite exhibits properties of plasticity and cohesion in between that of kaolinite and montmorillonite, and is a nonexpanding type (Hillel, 1980).

Atterberg Limits. The liquid and plastic limits of the soil were determined with the method recommended by the American Society for Testing and Materials (1988), procedure D4318-84. The liquid limit is defined as the moisture content at the boundary between the liquid and plastic states. The plastic limit is defined as the moisture content at the boundary of the plastic and brittle states. The moisture content desired for most effective deep tillage falls within the brittle state. The plasticity index is defined as the difference between the liquid and plastic limits. This index is an indicator of the soil's ability to flow plastically and is a function of the type and amount of clay present (Hillel, 1980). The soil's plastic limit averaged 18.8 %. The soil's liquid limit was determined to be 28.1 %. The plasticity index was 9.3 %. This defines the soil as having low to medium plasticity and low to medium compressibility (Terzaghi and Peck, 1962). Published data for a Belknap silt loam with respect to Atterberg limits were not found.

Particle Density. The particle density of the model soil was determined to be 2.03 g/cm^3 (126.9 lb/ft^3). The American Society for Testing and Materials (ASTM), procedure D854-83, was followed (American Society for Testing and Materials, 1988). Published particle densities for a Belknap silt loam were not found.

System Components

In order to satisfy the research objectives, a physical model was developed in the laboratory. The major pieces of equipment used in this experiment were:

1) soil bin,
2) air pallet,
3) Giddings soil probe,
4) tillage tool: ripper,
5) air and material injection unit: sandblaster,
6) nuclear density/moisture gage,
7) cone penetrometer and data acquisition system, and
8) permeameter.

The first five components are shown in Figure 5 and will be discussed in this chapter along with the soil analysis equipment.

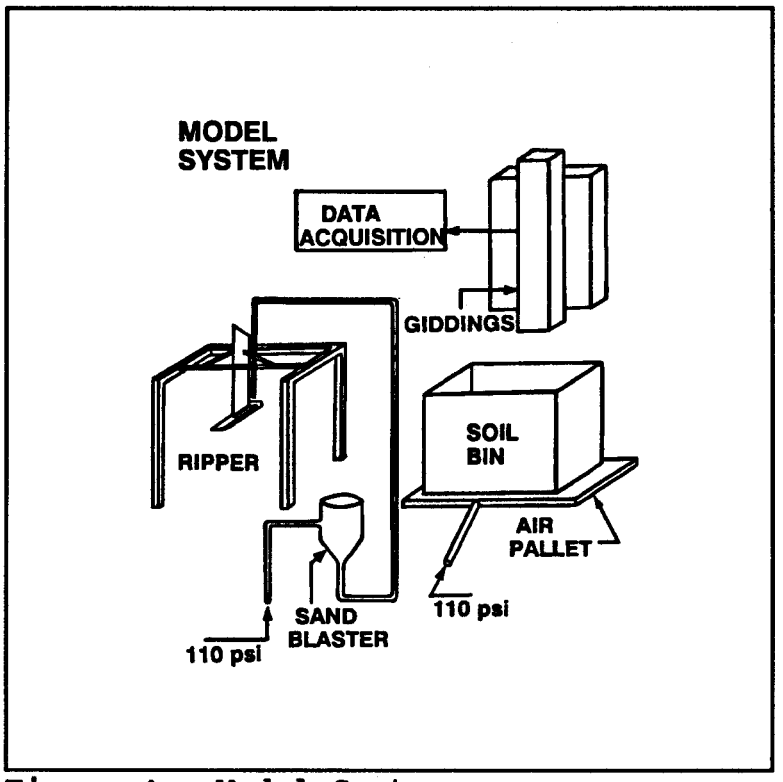


Figure 4 - Model System

Soil Bin and Air Pallet. A soil bin served as the containment unit and measured 91.4 cm by 121.9 cm (36.0 in. by 48.0 in.) in plan view and 91.4 cm (36.0 in.) deep. The bin was made of steel and designed to meet the needs of this project. The front and back panels were removable to facilitate soil removal. A small section was cut out of the front and back panel for ripper insertion and removal. The bin was positioned on top of an air pallet. The base of the pallet had four pads which provided an exit for pressurized air, which was applied in order to float and move the bin of soil. The bin was positioned with the air pallet as needed in order to compact the soil and to take soil samples and readings. When the bin was filled with compacted soil, its weight was 1.8 tonnes (2.0 tons).

Giddings Soil Probe. The Giddings soil probe was used for sampling for bulk density and hydraulic conductivity, driving the cone penetrometer, compacting and recompacting the soil. The maximum applied force was 22 kN (5000 lbs).

A flat plate was machined measuring 30.5 cm by 30.5 cm (12.0 in. by 12.0 in.) and 1.90 cm (0.75 in.) in thickness. The plate was threaded to a 2268 kg (5000 lb) pressure transducer, which was attached with a pin to the shaft of the Giddings. As the shaft was lowered, the soil was compressed under the plate. This resulted in activating the transducer, which sent a voltage to an amplifier and then to a computer to be digitally recorded. The maximum applied pressure available with the Giddings was 301.6 kPa (43.8 psi).

Tillage Tool Design. Due to the limited size of the soil bin, the volume of failure was determined in order to minimize the reaction with the bin walls. It was desired to leave a buffer of undisturbed area between the ripped zone and the bin walls. The important variables to be modeled were the ratio of the operating-depth-to-cutting-width of the ripping tool and angle of the ripper foot off the horizontal (rake angle). These two dimensionless ratios describe the phenomenon of soil failure. The area of surface disturbance was determined with the help of a mathematical model developed by Godwin and Spoor (1977).

The model ripping tool was selected to loosen the soil within the confines of the bin with an operating depth of approximately 30 cm (12 in.). To minimize the reaction with the bin walls, the edge of the surface disturbance extended approximately 30 cm (12 in.) on either side of the ripper. A buffer of undisturbed area, measuring approximately 40 cm (16 in.), was located between the bin wall and the ripped zone on each side of the ripper.

A standard farm implement (Fred Cain subsoiler) was selected. The ripper was mounted on a frame and pushed with a hydraulic cylinder which had a stroke of 91 cm (36 in.) and a maximum applied force of 218 Kn (49,000 lbs). The model ripper had a depth-to-width ratio of approximately 5.5 (i.e., 27.9cm/5.1 cm (11.0 in./2.0 in.)). Typically, the soil surface was approximately 2.5 cm (1.0 in.) below the top of the bin. The angle of inclination of the ripper leg and foot (as a rigid body) was adjustable. The angle between the leg and the foot was $.628\pi$ rad (113 $\circ$) (i.e., when the ripper leg is vertical, the ripper foot makes an angle of $.128\pi$ rad (23 $\circ$) off the horizontal). The ripper foot was machined with an inverted "V" shape at the rear. The material injection hose was located just above this inverted "V" shape to potentially enhance material dispersion into the crescent failure area, as shown in the figure discussed below. The ripper had a velocity of approximately 1.2 cm/s (.48 in./s), which may reasonably develop failure patterns similar to field ripping speeds, as discussed by Stafford (1979).

Air and Material Injection Unit Design. The function of the air and material injection unit was to fill the void space caused by deep tillage with material. If the filling of these cracks and crevices is effective in reducing or preventing recompaction, then initially the design should attempt to fill as many fractures as possible. However, it is unlikely that all of these voids will be filled by the injected material, since a direct path to the void may not be available. The porosity of the soil after deep tilling was found for the baseline trial and was used to determine the amount of injection material needed to fill all available void space created by deep tillage. A commercially available sandblaster, manufactured by Schmidt Mfg., Inc., was capable of delivering 21 kg (47 lb), or 70 % of the maximum design amount, of slag product during each ripping event.

The sandblaster is a tank in which pressurized air enters near the top and, working with gravity, forces material through the funnel-shaped outlet at the base. The material is then pneumatically conveyed through the hose. The base of the sandblaster was funnel-shaped with an angle of $.22\pi$ rad (40$\circ$) off the horizontal. A valve was located at the base of the sandblaster to meter material through the hose. The volume of the blaster was .04 m^3 (1.50 ft^3). The available laboratory air line pressure was 758 kPa (110 psi). The sandblasting hose was downsized with a tapered fitting so that the hose could fit behind the ripper leg. The hose outlet was located at the rear of the ripper immediately above an inverted "V" shape, which was machined on the ripper foot. To prevent an excess of material exiting the path of the ripper, a shield was also machined as a part of the ripper foot. The inside diameters of the sandblasting hose and ripper hose were 3.18 cm (1.25 in.) and 1.3 cm (.5 in.), respectively. Figure 6 shows the system used to inject material pneumatically.

Initially, the material typically used for sandblasting was also used in this experiment (i.e., slag product). Other granular materials that flowed freely and had an angle of repose less than the inclination of the base of the sandblaster were located and subsequently used in this experiment. Standard procedures to determine particle density and bulk density of the injection materials shown in Table 3 were not found.

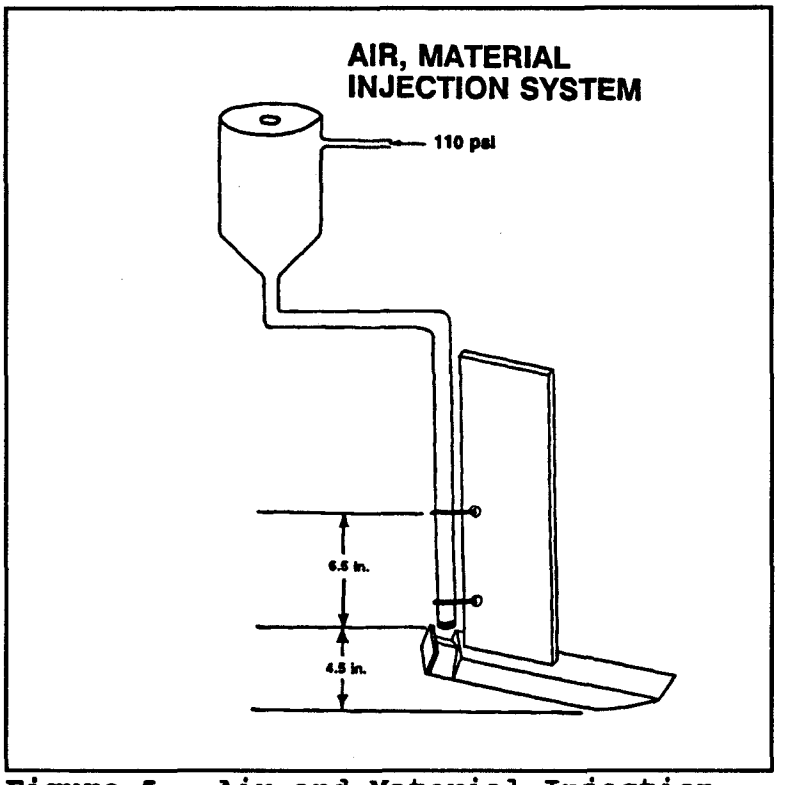


Figure 5 - Air and Material Injection System

Table 3
Injection Material Characteristics

Type of Material	Sieve Size openings passed- retained (cm) (in.)	Particle Density $(g/cm)^3$	Bulk Density (g/cm^3)	Angle of Repose (°)
Slag Product	30-51 12-20	2.42	1.48	34
Walnut Shells	51-76 20-30	1.32	.63	34
Pecan Shells	30-51 12-20	< 1.0	.62	36

Table 3 shows the particle density of the walnut shells to be greater than that of the pecan shells. Yet, the bulk densities, as measured in the loosened state, were nearly the same. Notice that the walnut shells have a slightly wider range of particle sizes as compared to the pecan. Recall that a

wider range of soil particle sizes generally packs more easily (Gupta and Larson, 1979). Thus, the walnut shells may be expected to compact to a higher density.

The amount of injected materials needed to fill all available pore space for the selected materials are shown in Table 4.

Table 4
Injection Material Amount

Material Type	Amount of Material kg (lbs)
Slag Product	30 (65)
Walnut Shells	13 (28)
Pecan Shells	13 (28)

Slag is a byproduct of blast furnaces. To reduce iron ore to iron, the furnace requires coke, iron ore and limestone. Molten iron and slag result from the oxidation of the coke. Productive uses of the slag byproduct include use as an abrasive material in a sandblaster. When a less abrasive material is needed, ground walnut shells or corn cobs are used. Ground pecan shells are used as a decorative material in model train landscapes.

Revisions to the Workplan

A few minor revisions to the workplan were found to be necessary. These revisions did not affect materially the outcome of the project. It was proposed that one of the test bins would be compacted using a rubber tire that was part of a model in the Agricultural Engineering Laboratory. However, due to the delays that the Department of Agricultural Engineering experienced in occupying their new building, this model was inoperative for an extended time and not available when it was needed during the project. This did not affect the laboratory results, since a datalogging system had been installed with a load cell to measure precisely the load that was applied for compaction and recompaction.

In was initially assumed that the air permeability of the soil would be evaluated along with the other parameters. However, it was decided that hydraulic conductivity would be simpler to measure and still indicate the presence of interconnected voids.

Finally, it was not possible to study the effects of freeze and thaw on recompaction. This was primarily due to a lack of equipment. The investigators requested no funds for equipment, selecting rather to procure the equipment independently. However, funding for the temperature-controlled chambers was not available and there was no access to other suitable facilities.

On the positive side, the soil characterization work and the thorough documentation of compactive effort through the use of the load cell and datalogging system exceeded the standard proposed initially. This resulted in very tight control on the compaction and recompaction phases of each test.

CHAPTER IV

EXPERIMENTAL DESIGN AND PROCEDURE

Experimental Procedure

This experiment was designed to determine the effect of material injection on the recompaction of prime farmland subsoil. A total of ten soil bins were prepared. The treatments consisted of:

1) air injection,
2) slag product injection,
3) walnut shell injection,
4) pecan shell injection, and
5) no injection (baseline).

The treatments were replicated twice. In order to assure homogeneity of the soil bins, pertinent factors were held as constant as possible throughout the process of replication. These factors were soil type, applied load for compaction and recompaction, soil moisture content, operating variables of the ripper such as depth-to-width ratio and rake angle, and loosened bulk density of the injection material. The area of study concentrated on the ripped zone. The number of samples extracted and readings taken were determined by the physical limitations of the soil bin (91.4 cm by 121.9 cm by 91.4 cm. (36.0 in. by 48.0 in. by 36.0 in.)) and the volume of the ripped zone.

In this chapter and those that follow, the terms 'bin' or 'soil bin' refer to the physical item. Usually, these two terms are used when describing the processing stages. The term 'trial' refers to a completed bin of soil that is in the stage of analysis. The term 'treatment' usually refers to the combination of two trials, which is the case for the walnut and pecan treatment. This term can be associated with either the bins of soil during processing or the trials during the analysis.

Method of Replication. Each bin of soil underwent three stages:

1) Initially compacted,
2) Ripped and simultaneously injected with material, and
3) Recompacted.

After each stage, samples were taken for bulk density and hydraulic conductivity. In addition, readings were taken for mechanical resistance with a cone penetrometer and bulk density with a nuclear density/moisture gage. The amount of recompaction by natural settling due to gravity was considered negligible (Kouwenhoven, 1986). These measurements of compaction are an indication of the physical condition of the soil.

Initial Compaction. Moisture content and applied pressure were controlled as much as possible during the compaction process of each bin. In order to minimize variance due to the execution of the experiment, it was desired to use the same procedure for each bin.

The soil bin was filled approximately 8 cm (3 in.) at a time and water was added to bring the mass moisture content near optimum for compaction purposes (19.0 %). The soil was then mixed by hand to moisten uniformly all areas. To do this, half of the soil surface was lightly

sprinkled with water. The thin layer of wet soil was then raked to one side (one half) of the bin. The exposed dryer soil was then sprinkled and raked. This was repeated until a layer of soil measuring approximately 8 cm (3 in.) was moistened. Then the other half of the bin was moistened in a similar manner. The direction of raking was parallel to the direction of the ripper path, so that any potential dry area would occur perpendicular to the path of the ripper. This method reduces the area of potentially dryer soil that is affected by ripping.

The soil was compacted in approximately 15-cm (6-in.) lifts with the Giddings soil probe. This was accomplished by applying a vertical load distributed over a flat plate. The operator adjusted the controls on the Giddings soil probe as needed to maintain a constant reading on the digital output device located on the voltage amplifier. In addition, the applied load as a function of time was recorded on the computer monitor display. The soil bin was repositioned with the air pallet for each compaction location as shown in Figure 7.

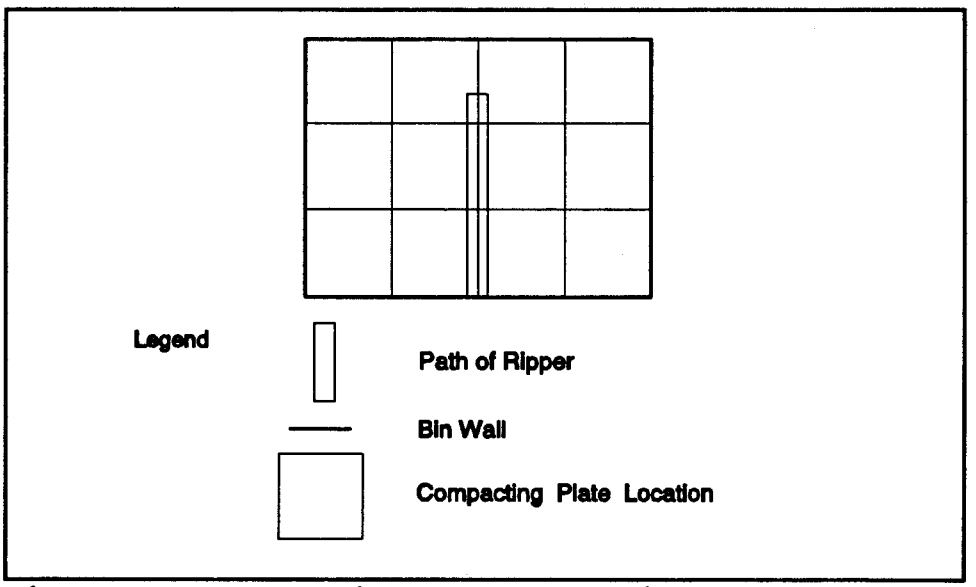


Figure 6 - Compacting Plate Locations

Since the maximum applied pressure available with the Giddings unit was 301.6 kPa (43.8 psi), typical reported ranges of pressures under scraper tires (551 to 860 kPa (80 to 100 psi)) could not be reached (Barnhisel, 1988). Typical dozer pressures, as tabulated by Barnhisel (1988), (31.7 to 152.2 kPa (4.6 to 22.1 psi)) were reachable with the Giddings unit. To obtain a worst case scenario, the upper part of this range was chosen. Therefore, the targeted pressure range under the compacting plate was set at 124-138 kPa (18-22 psi) and maintained for 60 seconds. However, due to the design of the experiment, maintaining consistent pressures among treatments was more important than the level of pressure selected.

Ripping. After initial compaction, the bin was repositioned in order to take samples and readings for the above mentioned parameters. The hose of the sandblaster was then attached to the ripper shank with the hose outlet located at the rear of the ripper foot. A small amount of material was run through the sandblasting hose to assure adequate conveying conditions. The valve at the base of the sandblaster was set at a predetermined level, which allowed for smooth flowing conditions, based on a visual inspection.

To prepare for ripping, the air pallet and the soil bin were moved to the ripper. Ripping was initiated by first applying pressurized air to the sandblaster and allowing the material to be deposited outside of the soil bin. This was done to assure continuous flow through the injection hose. The ripper was then engaged, and pushed through a slot in the soil bin with a hydraulic cylinder. Material was injected into the soil with the sandblaster while being ripped. Due to the expansion of the pressurized air, some of the material was expelled from the soil bin. Most of the expelled material was discharged horizontally in a direction opposite of ripper advance. A small amount of material was discharged vertically from the path of the ripper. Usually, the material stopped exiting the bin when the ripper was about one-third to one-half of the way through the bin.

The hydraulic cylinder reached the end of its travel length at approximately 20.3 cm (8.0 in.) from the wall of the bin. At this point, material injection ceased and the ripper was removed from the bin by hoisting vertically. A wedge of soil that formed in front of the ripper was also removed. This created a cavity near the bin wall.

The weight of the material in the sandblaster was noted prior to ripping and again after ripping to determine the amount of injected material. Also, the material deposited on the floor of the laboratory was collected to give a better estimate of the material injected.

The walnut shells, pecan shells, and slag product cost approximately $264.00, $7.50, and $4.60 per 45 kg (100 lb) bag, respectively.

Recompaction. The soil was then recompacted at a targeted pressure of 75.8 to 89.5 kPa (11.0 to 13.0 psi) and maintained for 30 seconds. This range was determined by a typical pressure range found under a Caterpillar dozer track (78.5 to 88.8 kPa (11.4 to 12.9 psi)). However, the selection of this pressure range was not as critical as maintaining consistency among treatments. The transducer used to document initial compaction and recompaction is discussed later in this thesis.

Excavation. After all samples were taken, the soil in the ripped zone was excavated with a hand spade, examined for injected material and discarded. The gravimetric core holes and cone penetrometer holes were located in the ripped zone using their recorded coordinates. Most of the holes were still evident in the ripped zone when excavating. Those that pierced the injected material were noted for future analysis. The top 61 cm (24 in.) of the model soil were then shoveled out of the bin. The lower 30 cm (12 in.) were left in the compacted state in the bin bottom.

Moisture Content

The optimum moisture content of the soil for compaction purposes was determined by the Proctor compaction test and was found to be 19.0 %. This moisture level was selected for the initial compaction stage to ensure adequate compacting conditions. However, this moisture content is greater than one would select for ripping in actual field conditions, since a plastic flow, instead of the desired shattering effect, is likely to occur (Gill and Vanden Berg, 1968; Stafford, 1979).

Soil Analysis Techniques and Sampling Patterns

The soil characteristics measured were soil bulk density (by two methods), mechanical resistance, and hydraulic conductivity. Following is a discussion of the major components of the data analysis equipment, nuclear density/moisture gage, cone penetrometer, and permeameter.

Bulk Density. The two methods used to test for bulk density were the gravimetric method and nuclear gage method. Since the model soil was cohesive and free of rocks, the gravimetric method using core samples was chosen. This method is destructive, but had the advantage of retaining the sample for further analysis with the permeameter. Moreover, this method was limited by the possibility of not sampling the injected material. The location of the injected material in the failure zone was unknown during gravimetric sampling. However, it was fairly certain, after one bin excavation, that the majority of the injected material was located in the path of the ripper. The nuclear gage method had the advantage of taking many density samples perpendicular to the ripping path. This ensured that readings were taken in the area of material injection.

Gravimetric. The method, as described by the American Society for Testing and Materials (ASTM), procedure D2937-83, is not appropriate for sampling friable soils with low plasticity which will not be readily retained in the cylinder (American Society for Testing and Materials, 1988). The soil in the ripped zone was not satisfactorily retained in the drive cylinder, unlike the soil in the initially compacted area. A basket retainer was necessary to increase soil retention in the ripped zone. This precluded the use of a thin-walled cylinder. Furthermore, it was desired to use the same equipment for all gravimetric bulk density sampling. Soil core samples were taken with a split-barrel sampler, sliced, measured, weighed, oven-dried and reweighed to obtain density and moisture readings, gravimetrically. Duplicate samples were taken from each 15.2-cm (6.0-in.) layer down to 45.7 cm (18.0 in.).

The mass moisture content of the soil was measured gravimetrically. The American Society for Testing and Materials (ASTM), procedure D2216-80, recommends an oven temperature of 110 +/- 5 °C (230 +/- 1 °F) (American Society for Testing and Materials, 1988). Maximum available oven temperatures were 45 °C (113 °F). To compensate for this, the drying time was increased until the mass after two successive periods (greater than 1/2 hour) of drying indicated an insignificant change in moisture content (less than .1 %), as recommended by above mentioned procedure. Typical sampling locations for gravimetric bulk density are shown in Figure 8. Also in this figure are locations for hydraulic conductivity, which will be discussed later.

Nuclear Gage. Gamma and neutron radiation were emitted from 10 mCi Cs-137 and 50 mCi Am-241/Be to measure wet bulk density and moisture content, respectively. Both sources were noncollimated. A dual probe strata density/moisture gage, usually referred to as "nuclear gage" or "gage" was used. The manufacturers model number was MCSA-00A with MC-S-36 software (CPN Corporation). The nuclear gage is shown in Figure 9.

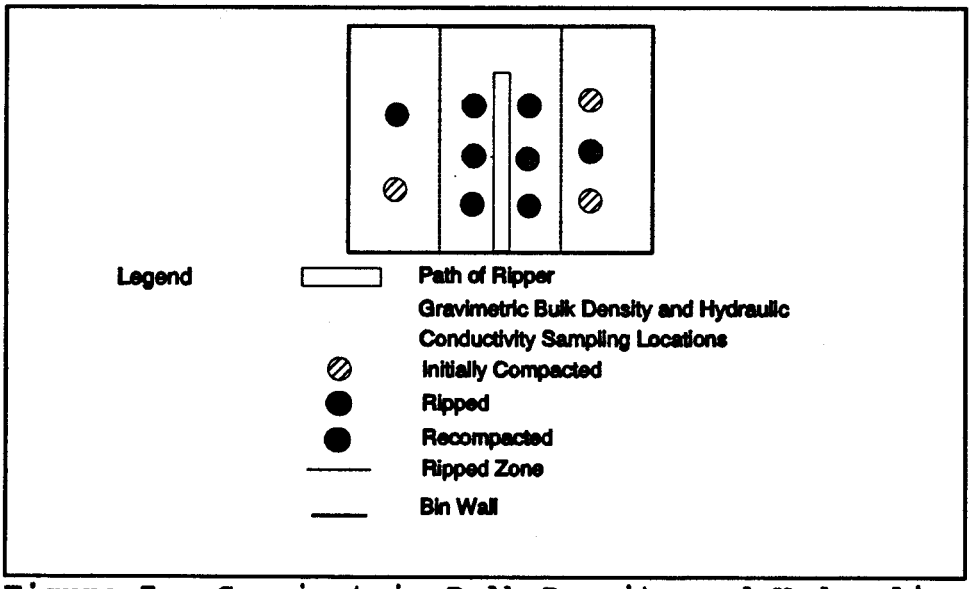


Figure 7 - Gravimetric Bulk Density and Hydraulic Conductivity Sampling Location

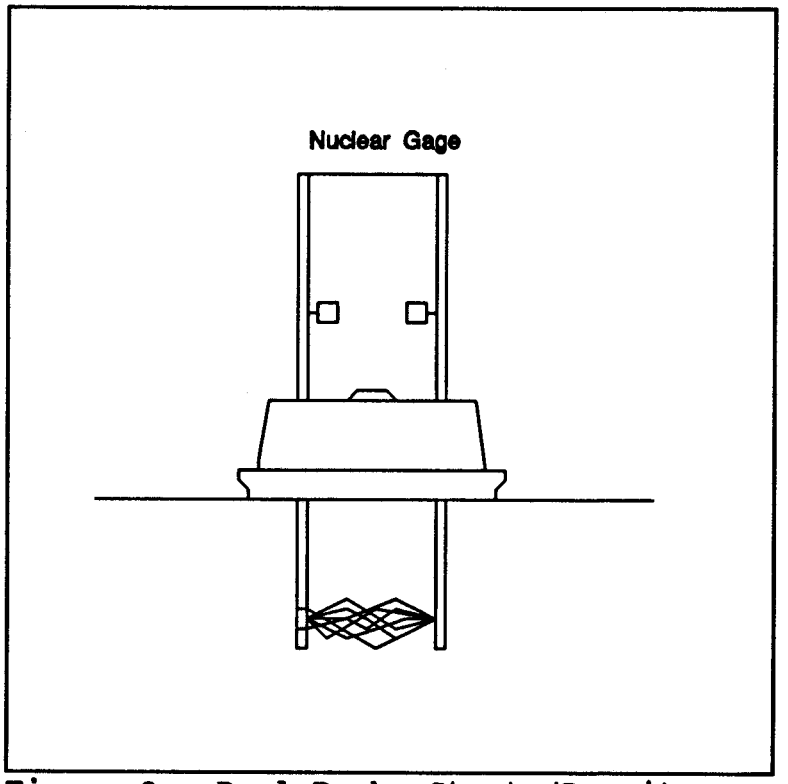


Figure 8 - Dual Probe Strata/Density Moisture Gage

The American Society for Testing and Materials, procedures D2922-81 and D3017-78, were followed, to determine the wet bulk density and moisture content, respectively (American Society for Testing and Materials, 1988). One minute measurements were taken simultaneously with a dual probe gage. The probes were located at least 30.5 cm (12.0 in.) from the walls of the bin, as recommended by the manufacturer. The above referenced American Society for Testing and Materials procedure recommends the probes be located at a distance of at least 22.9 cm (9.0 in.) away from any obstruction. The specification range of densities measured by this instrument was 1.12 to 2.73 g/cm^3.

The gravimetric moisture content was used to calculate the dry bulk density, given the wet bulk density as measured with the gage (CPN Corporation, 1988; Wells and Luo, 1991). The following equation was used:

$$DBD = WBD/(1 + C*MC)$$

where :

DBD = Dry Bulk Density (g/cm^3)
WBD = Wet Bulk Density (g/cm^3)
C = ratio of the mass attenuation coefficient of water to soil = 1.115
MC = Moisture Content (%)

The probes were lowered into the prepared access holes and duplicate readings were taken at 5-cm (2-in.) intervals down to 45.7 cm (18.0 in.).

The nuclear gage locations for the walnut treatment are shown in Figure 10. To increase data collection in the ripped zone, one additional nuclear gage location was selected for the pecan and the baseline treatments as shown in Figure 11.

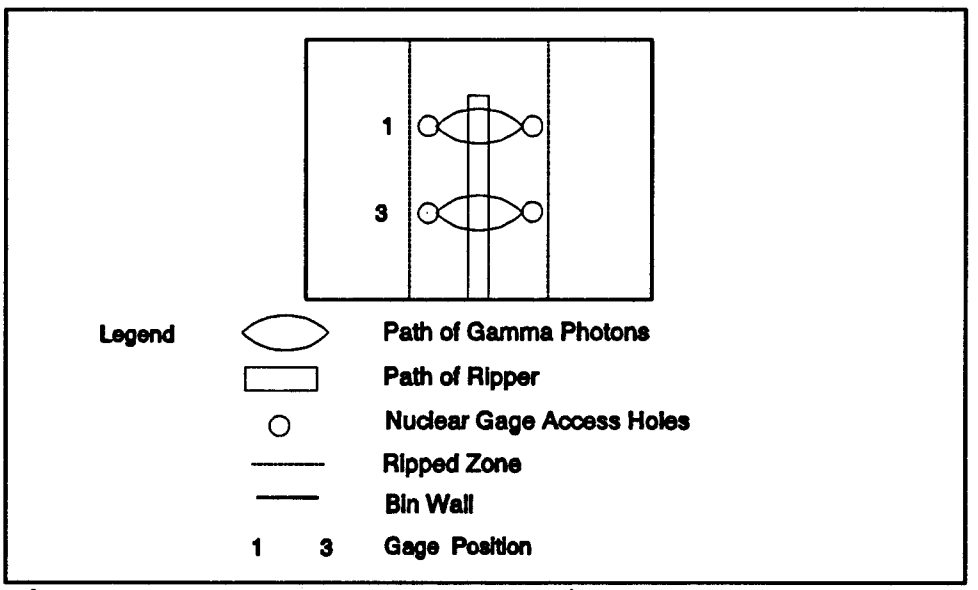


Figure 9 - Nuclear Gage Locations for Walnut Treatment

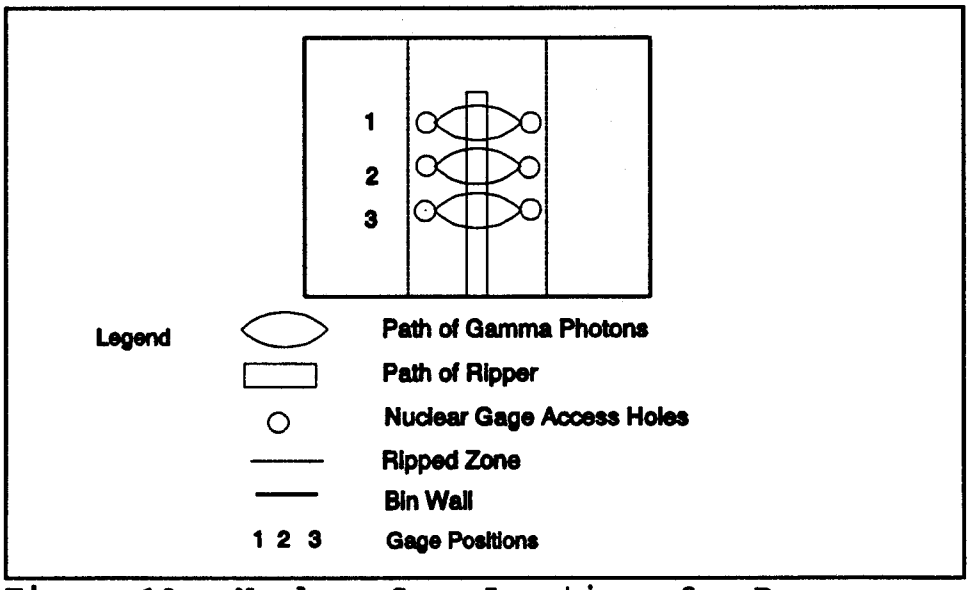


Figure 10 - Nuclear Gage Locations for Pecan and Baseline Treatment

Standard counts were taken at the start of each day's use. Since the radioactive decay influences the number of emitted photons, the decay also affects the determination of soil density. The standard count was taken by placing the nuclear gage on a block of polyethylene and conducting a four-minute count (allowing the detector to measure incoming photons for four minutes). The value of the standard count was stored in the nuclear gage memory as counts/minute and was used for determining soil density.

The precision of this instrument was determined by the square root of the actual accumulated counts divided by the slope of the calibration curve. This value was calculated for each reading.

Typical bulk density values for a silt loam soil that has been disturbed by mining activities range from 1.61 to 1.73 g/cm^3 and varies with the method of reconstruction (Barnhisel, 1986). Ranges of 1.63 to 1.75 g/cm^3 were reported by Albrecht and Thompson (1984) for a silt loam subsoil deposited by truck. A range of reported values for a silt loam soil after ripping under desired conditions were from 1.46 to 1.63 g/cm^3 (Barnhisel, 1986). After ripping and recompaction, an increase in bulk density of 1.9% in the ripped zone and 2.6% over the entire profile was reported by Barnhisel, (1986).

To calibrate the nuclear gage, densities of three blocks of material were used to obtain low, medium and high counts. The factory calibration used the following set of known block densities: 1.72 g/cm^3, 2.14 g/cm^3, 2.63 g/cm^3. The block densities were determined by the water displacement method using scales calibrated with the United States Bureau of Standards. In addition, the blocks were X-rayed to verify uniformity. Each block measured 35.6 cm (14.0 in.) by 45.7 cm (18.0 in.) by 61.0 cm (24.0 in.).

The CPN calibration was performed by taking, at each 5.1- cm (2.0-in.) depth, a count on the low, medium and high density blocks. These three measurements, plus the standard count were then fit to an equation of the form:

$$\text{Density} = B * \ln (A/(R-C))$$
$$\text{where } R = \text{Count/ Standard Count}$$

A, B and C Coefficients were determined for each 5.1-cm (2.0-in.) layer down to 20.3 cm (8.0 in.). Below 20.3 cm (8.0 in.) one set of coefficients was determined. This accounts for gamma photons that escape into the atmosphere at the shallow depths due to a noncollimated point source (CPN Corporation, 1988). The nuclear gage then used the coefficients in Table 5 to calculate the experimental soil density.

Table 5
Nuclear Gage Calibration Coefficients

Depth Below Surface (in.)	Coefficients		
	A	B	C
2	8.6416	37.5891	.0257
4	10.43924	36.15039	.02809
6	9.28677	38.71267	.00141
8 to 36	10.72264	36.49432	.02023

Mechanical Resistance. The resistance to penetration was determined with the cone penetrometer, which was driven with the Giddings hydraulic soil probe. A 454 kg (1000 lb) transducer was threaded to the shaft of the Giddings unit. A shaft and cone tip were then threaded to the transducer. The American Society of Agricultural Engineers, standard S313.2, was followed when operating the cone penetrometer (American Society of Agricultural Engineers, 1987). The tip of the penetrometer consists of a 30 degree right circular cone. The cross-sectional area of the base of the cone was 6.35 cm^2 (.98 $in.^2$) (Hooks and Jansen, 1986).

The resistance to penetration was found for a continuous interval of 45.7 cm (18.0 in.) and recorded on two devices. One device, a chart recorder, provided a hard copy in graphic form and the other device provided a digital computerized file. The data acquisition software, LABTECH, read 4 data points per second. At the standard penetration rate of 3.0 cm/sec (1.2 in./sec), one reading was taken every .76 cm (.30 in.). A typical plan view of the reading locations is shown in Figure 12.

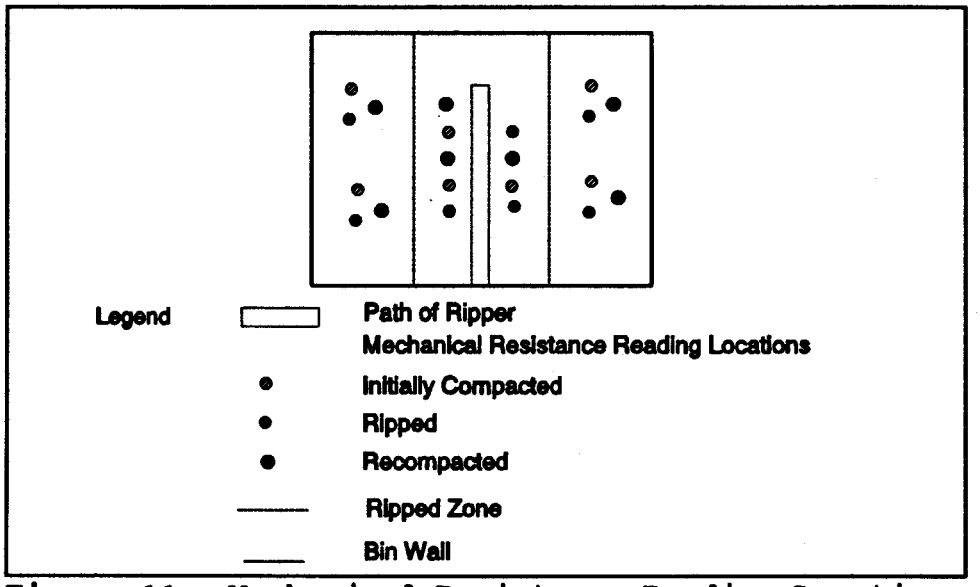


Figure 11 - Mechanical Resistance Reading Locations

Reported values of mechanical resistance as measured with a cone penetrometer for reclaimed mine soils range from .7 MPa to 3 MPa depending upon the soil handling method employed and the factors mentioned in previous chapters (Thompson, Jansen, and Hooks, 1987).

Calibration. Calibration of the transducer used for initial compaction and recompaction will be discussed concurrently with the calibration of the transducer used to document mechanical resistance readings. The two transducers were calibrated against known forces. The voltage output at a series of applied forces was recorded and used to calculate the relationship between force and voltage. The slopes and y-intercepts of these relationships were necessary inputs to the data acquisition package, LABTECH. This procedure was followed before and after data acquisition. The calibration curves used for compaction and recompaction are shown in the Appendix in Figure 19 and Table 13. The calibration curves used for mechanical resistance are shown in the Appendix in Figure 20 and Table 14. The output of the transducers were noticed to drift with time. Prior to each day's use, the transducer was zeroed (i.e., the voltage reading was adjusted to zero to correspond to no applied load).

In addition, the position of the Giddings head was recorded for a series of voltage outputs and used to calculate the relationship between distance and voltage. The slope and y-intercept of this relationship were also necessary input to the data acquisition package, LABTECH. Likewise, this procedure was followed before and after data acquisition. The calibration curves are shown in Figures 21 and 22 and Tables 15 and 16 in the Appendix.

Hydraulic Conductivity. The core samples of adequate size, which were taken for gravimetric bulk density were retained to be further tested for saturated hydraulic conductivity. It was desired to obtain one sample from each 15.2-cm (6.0-in.) interval down to 45.7 cm (18.0 in.). Due to the fragility of the samples taken in the ripped zone and the sample length requirement, this was not always possible. A minimum length of 5.1 cm (2.0 in.) was required to seat adequately the sample between the two platens. Commercially available distilled water was used as the permeating fluid.

Fluid conductivity testing has not been standardized for undisturbed, cored soil samples by the American Society for Testing and Materials (ASTM). These standards are currently being developed. The method and equipment used in this study to determine the saturated hydraulic conductivity closely resembled that of the proposed standard. The common aspects of the two methods are outlined below.

An impermeable, flexible membrane surrounded the sample, which was positioned vertically between two filter papers, porous plates and platens. The plates had a permeability of 3.16×10^{-4} cm/sec (6.23×10^{-4} ft/min), which was greater than the sample conductivity. The diameter of the platens, porous plates and the soil sample were nearly the same. The sample was located inside a cell which was nearly filled with tap water. First, a confining pressure was applied to the cell in order to maintain membrane-to-soil contact. The sample was initially saturated by applying a vacuum to pull distilled water through the sample. The saturation was continued by applying back pressure to force the distilled water through the sample and to reduce the amount of entrapped air. An increase in pressure will cause a reduction in the volume of gas bubbles in the water. For each degree of saturation, there is a corresponding pressure (back pressure) which, if applied to the pore fluid of the sample, will cause complete saturation. After the sample was saturated, the time for the flow of 0.100 cm^3 (6.0×10^{-3} $in.^3$) of distilled water was determined. The saturated hydraulic conductivity was found using Darcy's equation for fluid flow. After the determination of hydraulic conductivity, the sample was diced to examine for injected material. Typical sampling locations for hydraulic conductivity are shown in Figure 8, as previously mentioned. Hydraulic conductivity values reported for organic and inorganic soil (sands, silts, and clays) typically range from 10^{-3} to 10^{-7} cm/sec (Terzaghi and Peck, 1962).

CHAPTER V

EXPERIMENTAL RESULTS AND ANALYSIS

Due to the lag of equipment delivery at the beginning of the experiment, the effects of material injection in the experimental soil were measured by means of several methods, as shown in Table 6. A data acquisition system, which was used to monitor compaction and recompaction pressures, was available in the laboratory starting with Trial S2 shown in Table 6. Therefore, the pressures generated in trials one through five were not documented. Due to the inability to ensure relatively uniform compaction and recompaction, these first five trials were not included in the analysis. Also, in the first five trials of the experiment, the effects of the injected material were primarily quantified through gravimetric bulk density. Since the location of the injected material, other than in the ripper path, was unknown prior to sampling, quite often the soil sample did not contain any injected material (i.e. slag product). Therefore, most of this data did not represent the effect of the treatments applied to the soil. In order to measure the area of interest, a nuclear gage was utilized starting with Trial S2. For these reasons, the analysis of the experimental data excluded the bins of soil injected with slag product and air.

Table 6
Data Collection Summary

Trial Number	Gravimetric Bulk Density	Nuclear Bulk Density	Mechanical Resistance	Hydraulic Conductivity	Compacted and Re-compacted with Transducer
1 Baseline	X				
2 A	X				
3 A	X				
4 R-S	X				
5/S1 R-S	X		X		
6/S2 R-W	X	X	X	X	X
7/S3 R-W	X	X	X	X	X
8/S4 R-P	X	X	X	X	X
9/S5 R-P	X	X	X	X	X
10/B1 Baseline	X	X	X	X	X

A = Air tool inserted, not ripped
R-S = Ripped and injected with slag product
R-W = Ripped and injected with ground walnut shells
R-P = Ripped and injected with ground pecan shells
Baseline = Ripped, not injected with material

Nonetheless, these data are presented in the Appendix to document the experiment performed. The analysis of the experimental data included the bins of soil injected with walnut and pecan shells.

After the acquisition of the nuclear gage, gravimetric bulk density measurements were continued in order to document any potential treatment effects found in the ripped zone. In addition, mechanical resistance readings and hydraulic conductivity measurements were taken. However, many of the these data points, as before, did not represent the effect of the treatments applied to the soil due to the difficulty of sampling with assurance of intersecting the affected zone of depth. These data are presented in the Appendix to document the experiment.

The data obtained with the nuclear gage was analyzed statistically by the University of Kentucky Department of Statistics using the General Linear Models Procedure (Searle, 1987). Following is a detailed description of the analysis and criteria used to judge the soundness of the collected data.

Material Deposition

Most of the injected material was deposited in the path of the ripper in the lower half of the operating depth. Figure 13 shows the ripper foot and the corresponding nuclear gage probes.

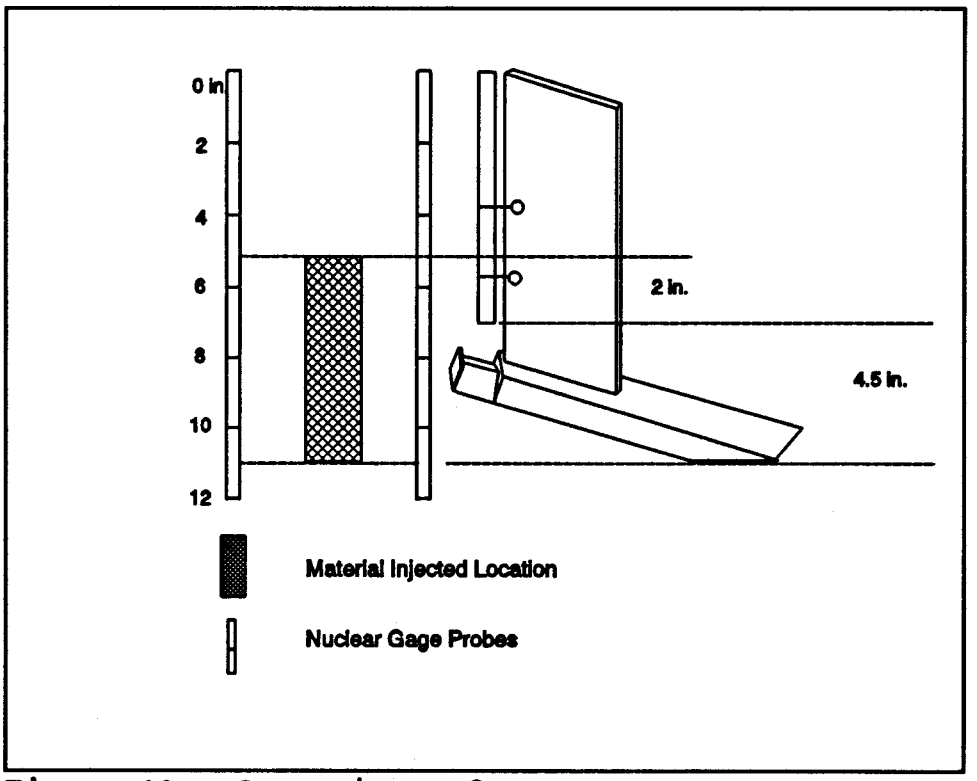


Figure 12 - Comparison of Injected Material Location and Ripper Configuration

Usually, the majority of the material was deposited in a continuous mass from the depth of ripper penetration to approximately 5 cm (2 in.) above the hose outlet. The depth of ripper penetration usually ranged from 25.4 - 27.9 cm (10.0 - 11.0 in.) below the surface of the soil. This locates the injected material at approximately 12.7 - 28.0 cm (5.0 - 11.0 in.) below the soil surface. The dimensions shown in Figure 13 are approximate. Several short contiguous fingers of injected material were found emanating from the path of the ripper. These fingers ranged from 2.5 to 10.2 cm (1.0 to 4.0 in.) and were located approximately 15.2 to 20.3 cm (6.0 to 8.0 in.) below the surface of the soil. This corresponds to the approximately the location of the hose outlet. A thin layer of material was also found outside of the ripper path and was erratically deposited on curved planes of cleavage in the ripped zone. This layer consisted of dust-like particles and grains of nutshells. The thickness of the layer was equal to the average diameter of a grain of injected material. The deposition was typically patchy and unpredictable.

The pecan treatment was noticed to have a more continuous distribution of material than the walnut or slag product. This may have been due to the average particle size and the material's ability to be forced through the fractures created by tillage. For material transported by liquid, the crack width should be 2.5 to 3 times the maximum grain diameter in order to prevent blockage (Howard and Fast, 1970). Recall that the slag product and the pecan shells were the same size and both were smaller than the walnut shells. However, the slag product was shaped irregularly. The pecan and walnut shells were rounded. Figures 14 through 17 show the deposition of material for the walnut and pecan treatments.

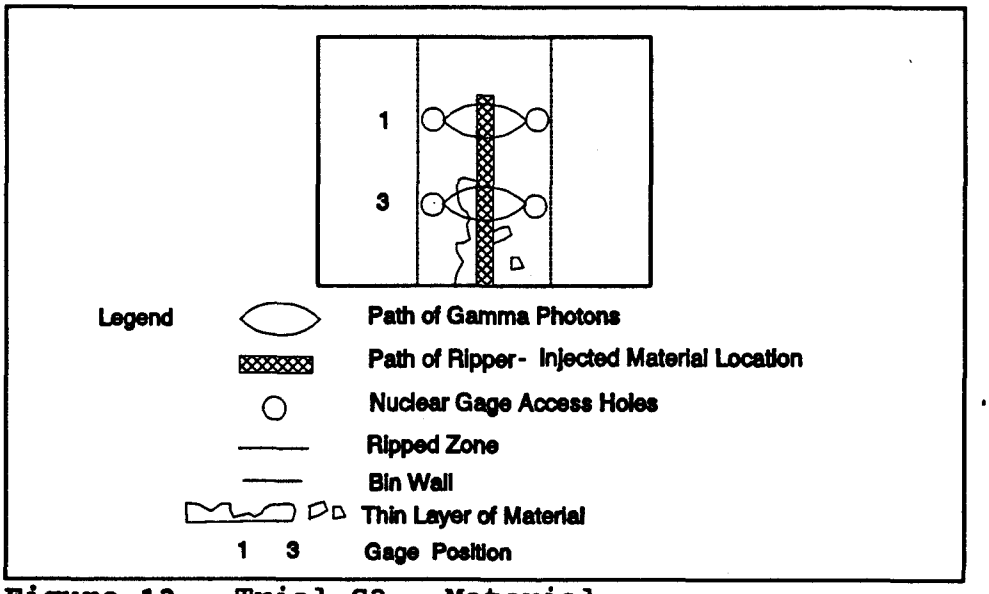


Figure 13 - Trial S2 - Material Deposition Walnut

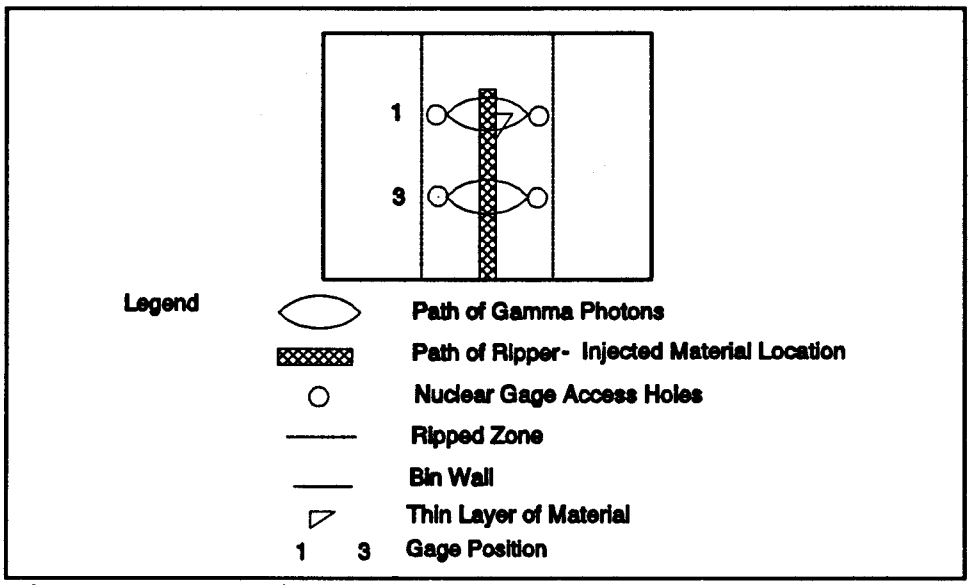


Figure 14 - Trial S3 - Material Deposition Walnut

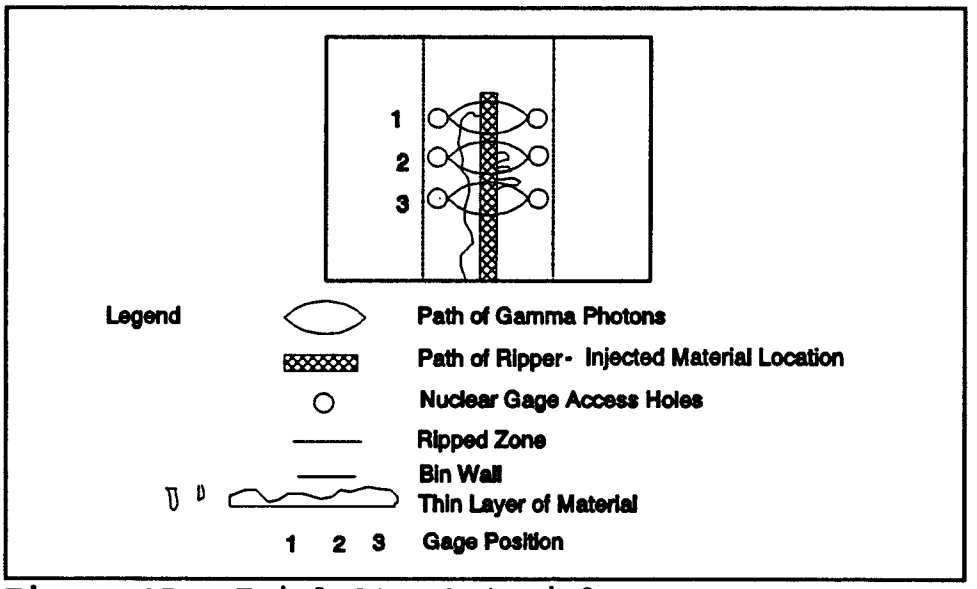


Figure 15 - Trial S4 - Material Deposition Pecan

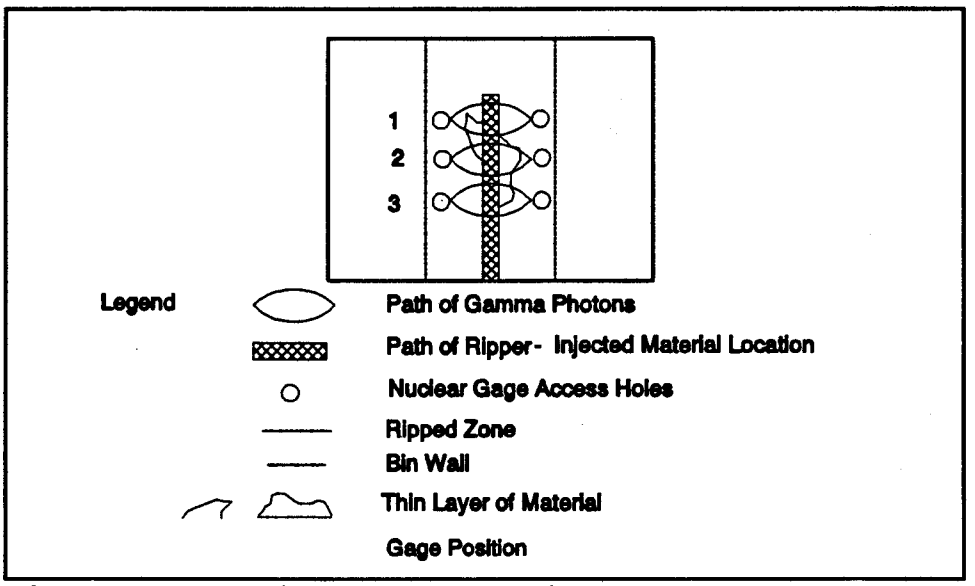


Figure 16 - Trial S5 - Material Deposition Pecan

Table 7 shows the amount of injected material for each bin of soil. Uniformity of the amount of injected material was desired. However, this was not always the case. This was due to the difficulty of separating the material that was run through the hose just prior to ripping with the material that was discharged from the bin during ripping. In addition, the material that was deposited throughout the laboratory during ripping and collected after ripping generally did not include all of the material available on the floor. It was estimated that an average of 28% of the material that was run through the conveying hose during ripping remained in the soil. Much of the discharged material was due to the start-up conditions. Recall that the ripper was pushed through the a slot in the bin wall. The first few seconds of ripping caused much of the material to be deposited outside of the bin. Therefore, this estimate does not reflect the anticipated percentage of material remaining in the soil from field applications.

Table 7
Injection Material Summary

Trial	Type of Shell	Injected Material g/lbs
S2	walnut	8172/18
S3	walnut	908/2
S4	pecan	8172/18
S5	pecan	1816/4
B1	none	NA

Factors Affecting Initial Compaction and Recompaction

Table 8 shows the applied contact pressures and moisture contents for each bin of soil in the top 30.5 cm (12.0 in.). The pressures were averaged over the nuclear gage locations. The moisture contents were averaged over each layer of soil measuring 15.2 cm (6.0 in.) in thickness. Uniformity of the applied pressures and moisture contents were desired for each bin of soil. However, some variation was found to exist.

The initially compacted pressures for the trials fell within a range of 11.7 kPa (1.7 psi). The initially compacted moisture content fell within a range of 2.5%.

The recompacted pressures for the trials fell within a range of 10.5 kPa (1.5 psi). The recompacted moisture content fell within a range of 2.3%.

Table 8
Contact Pressure and Moisture Content Summary

Trial Treat-ment	y Initially Compacted		Recompacted	
	Average Pressure Over Gage Locations kPa (psi)	Average Moist-ure Content (%)	Average Pressure Over Gage Location kPa (psi)	Average Moisture Content (%)
B1 Base-line	125.2 (18.2)	18.8	88.2 (12.8)	18.2
S2 Walnut	133.6 (19.4)	20.1	87.4 (12.7)	18.7
S3 Walnut	122.0 (17.7)	21.3	88.1 (12.8)	20.5
S4 Pecan	123.7 (18.0)	20.8	81.4 (11.8)	18.6
S5 Pecan	123.6 (17.9)	19.7	77.7 (11.3)	18.3

Methods of Sampling

The difficulty of measuring the effects of the injected material was seen in several methods of sampling. Soil measurements that were taken vertically included gravimetric bulk density, hydraulic conductivity, and mechanical resistance. These were aimed at measuring any injected material found in the ripped zone, excluding the ripper path, as explained below.

Generally, the resistance to coring or penetration was very low in or near the ripper path.

This caused the instrument to veer substantially, which resulted in an unacceptable sample or reading. Also, the coring tube diameter was approximately the same size as the width of the ripper foot, so that only noncohesive nutshells were sampled in the path of the ripper. Any core samples extracted in or very close to the ripper path were not competent to withstand subsequent handling and measurement. Therefore, the tabulated measurements, excluding nuclear bulk density, were taken outside the ripper path in or near the location of a thin layer of injected material. Thus, it was difficult to retrieve a sample that contained enough injected material to be considered of consequence. This qualitative judgment was reached based on visual inspection of the sample after the measurements were taken and visual inspection during excavation. Due to these reasons, several sampling methods generally did not serve the purpose of measuring the effect of the injected material. These were mechanical resistance, gravimetric bulk density and hydraulic conductivity. However, it was noted that Blackwell et al. (1989) were successful in taking gravimetric core samples in gypsum-enriched slots after recompaction.

The nuclear gage was the primary method available to measure soil density in the area of interest as shown in Figure 18.

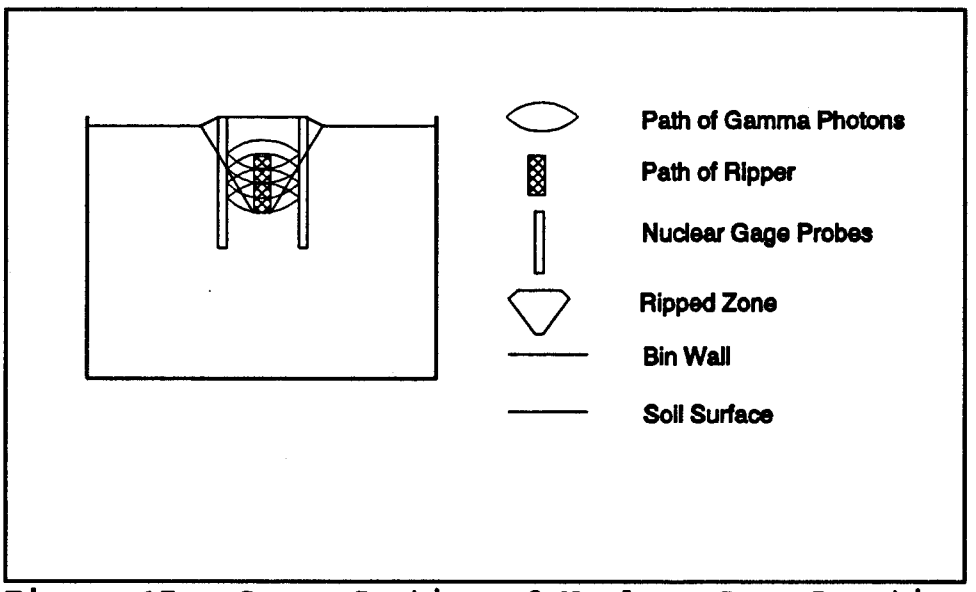


Figure 17 - Cross Section of Nuclear Gage Location

In addition, many measurements of the soil profile could be obtained over a relatively short distance. Due to the limited depth of tillage and subsequently small volume of soil failure, it was important to maximize readings over a distance of approximately 30.5 cm (12.0 in.).

Nuclear Bulk Density. Recompaction is defined, in this thesis, as the tendency of the soil to return to its original physical stage when acted upon by an outside force after tillage operations. For each stage of soil manipulation, the nuclear gage probes were lowered to nearly the same physical location. This enabled a direct graphical comparison of the soil profiles for each stage of soil manipulation. Also, the difference in bulk density from the initially compacted stage to the recompacted stage was analyzed graphically. As this difference in density increases, the amount of recompaction decreases. However, the statistical analysis involved the absolute magnitude of the recompacted values.

Recall that nuclear bulk density was determined for each 5.1-cm (2.0-in.) interval down to a depth of 45.7 cm (18.0 in.). The use of the nuclear gage was advantageous since the probes were placed on either side of the ripping path, perpendicular to the direction of travel of the ripper. Thus, it was fairly certain that the densities monitored in this fashion included the in situ density of the injected material.

The resulting bulk densities were generally lower than found in most field situations (Barnhisel, Powell, and Hines 1986). This was due to the limitations of the laboratory equipment available for compaction.

Graphical Analysis. Figures 26 through 30 in the Appendix show the soil profiles for each stage of soil manipulation for each trial. Tables 20 through 24 correspond to the soil profiles. Due to a few missing values at the 45.7 cm (18.0 in.) depth, this level was not reported. A comparison of Figures 26 through 30 in the Appendix shows that the walnut trials were initially compacted slightly higher than the pecan trials. Both the walnut and pecan trials were initially compacted higher than the baseline treatment.

The walnut treatment shows higher density values in the upper 10.2 cm (4.0 in.) of the ripped zone than either of the other two treatments. This may be due to site preparation of the access holes. A level area was needed in order to prepare access holes for the gage probes so that the holes were oriented vertically. Initially, this was accomplished by setting the guide-plate on the ripped area without prior preparation. Starting with Trial S4, the first pecan treatment, the top few centimeters of the ripped zone were removed with a hand spade and a level area was constructed. Then the guide-plate was carefully placed on the area. This may have resulted in a decrease in density in the upper layers of the soil profile for the pecan and baseline treatments.

The difference in density between the initially compacted and the recompacted stage was found in order to display graphically the amount of recompaction occurring.

The difference between initial compaction and recompaction of the soil density profile at each gage location was constructed from 5.1 cm (2.0 in.) to 40.6 cm (16.0 in.) for each trial. This is shown in the Appendix in Figures 31 through 35. Tables 25 through 29 correspond to the respective figures. At a depth of 25.4 cm (10.0 in.) below the soil surface, a lower density was found in the walnut treatment as compared to the adjacent layers (above and below). This was evident in three out of four nuclear gage location profiles. Position 1 in Trial S2 does not show this trend.

A trend was apparent in both pecan replications (Trials S4 and S5). Position one of the gage recompacted to a greater extent than positions two or three. Recall that the hydraulic cylinder reached the end of its travel path when the rear of the ripper foot was located approximately 20.3 cm (8.0 in.) away from the bin wall. At this point material injection was discontinued and the ripper was raised vertically out of the bin. The wedge of soil that formed in front of the ripper was also removed with the ripper. This created a small void near the bin wall. Also recall that the nuclear gage was located at 30.5 cm (12.0 in.) away from the wall of the bin. These factors may have contributed to the increase in recompaction at nuclear gage position one. This trend was not apparent in the walnut or baseline treatments, even though the same procedure was used when ripping. The walnut treatments may have been influenced by inadvertent compaction during site preparation when using the nuclear gage as explained previously. There was no noticeable reason for the baseline treatment to act similarly.

Figure 36 in the Appendix shows the average change in density from the initially compacted

state to the recompacted state for all trials. Table 30 shows the values of Figure 36. If the soil was recompacted to the maximum extent, a change of zero would result. The pecan trials show the least amount of recompaction. From Table 8, the pecan trials were found to be recompacted at the lowest average pressure. Figure 36 in the Appendix shows the walnut trials were recompacted to the greatest extent. From Table 8, both walnut trials were found to have higher recompacted pressures than the pecan trials, but slightly less than the recompacted pressure of the baseline trial. Referring again to Figure 36 in the Appendix, which shows the difference in initially compacted and recompacted density, the baseline trial falls approximately between the pecan and walnut trials. Below the level of ripping, the bulk densities generally increased above the initially compacted state. Similar results have been documented extensively (Cooper, 1971). Only one, Trial S2, did not recompact to a level higher than the initially compacted state below the depth of tillage.

Statistical Analysis. The recompacted values (response variable) were analyzed statistically at depths ranging from 10.2 - 25.2 cm (4.0 - 10.0 in.). From the soil profiles and Figure 13, this depth range appears to be the primary area of interest. The minimum acceptable level of significance was set at 10 %.

During data collection, the factors that had potential to influence the recompacted soil density observations were:

1) Treatment;
2) Physical location within the soil bin; and
3) Variables not fully controlled in the execution of the experiment.

Since location is defined by both position on the soil surface and depth below the soil surface, the controlled factors were treatment, position of the nuclear gage and depth of the probes below the surface of the soil.

For the purpose of an ideal design, many bins of soil should be processed and set aside prior to the application of treatment. This would allow for a measurement of the initially compacted density and other uncontrollable variables, which provides information for grouping the bins into blocks that are homogenous with respect to these variables. Then complete randomization should be carried out on each group or block of bins. However, out of necessity, many bins of soil could not be prepared and the blocks of soil bins could not be grouped prior to the application of treatment since only one metal bin and one air pallet was available in the laboratory. Instead, each bin of soil was processed and received exactly one treatment, sequentially. Complete randomization of the treatment, position and depth factors was not possible. Because of this, the experiment was analyzed using a split-plot model with covariates (Hicks, 1982).

Split-plot designs are most effective for experiments when one factor requires larger experimental units than another factor. This was the case when obtaining many samples within the same soil bin. The large experimental unit, or "whole plot" was defined as the soil in the entire bin and its corresponding factor was the treatment. Each trial was represented as a plot. The smaller experimental units or "split plots", were represented by smaller volumes of soil within the bin and the corresponding factor was gage position and depth below the soil surface. The treatment, a main effect, was confounded with plots, since only one treatment could be applied to the soil at a time. If the processing of a bin of soil changes from one plot (bin) to another, the effect of these changes will show up as differences between the treatments. Confounding means that the treatment effect cannot be estimated independent of the effect of the plots, as shown below: $T_i = T_{true} + P$
where:

T_i	=	effect of treatment i
T_{true}	=	true effect of treatment
P	=	effect of plots

The other two main effects, location and depth, were not confounded. This was necessary due to the physical limitations of the laboratory equipment.

As noted above there were independent variables, or covariates, that have potential to influence the recompacted density. Covariates are measured variables that are not the objective of investigation in the study. However, they may affect the response variable and they can not be fully controlled in the execution of the experiment. These variables were moisture content in the recompacted stage, initially compacted soil density, and recompacted pressure. The recompacted density values were adjusted to compensate for these effects. The form of the linear model with covariates was:

$$Y_{ijkl} = \mu + \beta_1(C1-\overline{C1}) + \beta_2(M2-\overline{M2}) + \beta_3(P2-\overline{P2}) + T_i + Tr_j(T_i)$$

$$+ P_k + T*P_{ik} + D_l + T*D_{il} + P*D_{kl} + \epsilon$$

where :

Y_{ijkl}	=	Value of the observation (recompacted density)
μ	=	mean of observations
β_1	=	slope of best fit line: initially compacted density versus recompacted density
C1	=	initially compacted density
$\overline{C1}$	=	average initially compacted density
β_2	=	slope of best fit line: recompacted moisture content versus recompacted density
M2	=	recompacted moisture content
$\overline{M2}$	=	average recompacted moisture content
β_3	=	slope of best fit line: recompacted pressure versus recompacted density
P2	=	recompacted pressure
$\overline{P2}$	=	average recompacted pressure
T_i	=	effect of treatment i
$Tr_j(T_i)$	=	trial within treatment interaction
P_k	=	effect of position k
$T*P_{ik}$	=	interaction of treatment and position
D_l	=	effect of depth l
$T*D_{il}$	=	interaction of treatment and depth
$P*D_{kl}$	=	interaction of position and depth
ϵ	=	error

subscripts:

i	=	treatment i, i = 1, 2, 3 (baseline, walnut, pecan)
j	=	trial j, j = 1, 2
k	=	position k, k = 1, 3
l	=	depth l, l = 1, 2, 3, 4 (10.2, 15.2, 20.3, 25.4 cm (4.0, 6.0, 8.0, 10.0 in.) below the surface)

Figure 24 in the Appendix shows a scatterplot of the recompacted moisture content versus the recompacted density. Corresponding values are shown in Tables 17 and 18. Due to a high moisture content in Trial S3, moisture was found to be a significant predictor of recompacted density ($p < .002$). In addition, the initially compacted density was found to be a significant predictor of the recompacted density ($p < .002$), although its effect was not as pronounced as the effect of moisture. Figure 25 and Tables 19 and 18 in the Appendix shows the relationship between the initially compacted versus recompacted density. Note that the fitted lines shown in Figures 24 and 25 do not have the same slope as given in the model stated above. The figures in the Appendix show the best fit line when considering each covariate one at a time, whereas the model above considers all covariates simultaneously.

The two-way interactions involving depth were not found to have a large influence on the recompacted density. However, the treatment and position interaction was found to influence the recompacted density values ($p < .02$). This was confirmed by the position component of the model, which was also found to be a significant predictor of recompacted density values ($p<.001$). This may have been due to the fact that the ripper was removed near position one and consequently material injection was stopped. The recompacted pressures were not found to be a predictor of the recompacted densities.

The R^2 value of the experimental model was 0.86. The model accounts for approximately 86% of the variation in the response variable (recompacted density). The precision of the experiment was reasonably good (C.V. = 2.71 %).

Tables 9 and 11 provide summary information after adjusting for recompacted moisture and initially compacted density with the response variable being recompacted density. Table 9 shows the analysis of variance and Table 11 summarizes the treatment means.

It was hypothesized that the propping effects of the injected material will reduce, or prevent, the recompaction of a deep-tilled soil. The null hypothesis states that the propping effects of injected material have no influence on the recompacted density values. Table 10 shows the test of the hypotheses using trial within treatment interaction as an error term. This term is an indicator of the differences of the trials within the treatments. By doing this, one assumes the trial within treatment interaction effect is zero and the sum of squares for this effect becomes a measure of error. The low F value for the interaction effect, Tr(T), in Table 9 justifies this assumption. Dividing the sum of squares obtained for the treatment by the sum of squares obtained for trial within treatment interaction in Table 9, the resulting F value was 5.32 with a probability of exceeding this value of .158. Therefore, the results obtained in this experiment, or better, will occur approximately 15.8 % of the time, by chance. Thus, the level of significance found in this experiment was 15.8 %. The acceptable level of significance was set at 5%. Therefore, the null hypothesis was accepted.

Table 9
Analysis of Variance After Recompaction

Source *	Degrees of Freedom	Sum of Squares	F Value	Pr > F
Model:				
C1	1	0.0223	13.51	0.0019
M2	1	0.0429	25.93	0.0001
P2	1	0.0000	0.00	0.9594
T	2	0.0453	13.68	0.0003
Tr(T)	2	0.0085	2.57	0.1058
P	1	0.0142	8.60	0.0093
T*P	2	0.0167	5.06	0.0188
D	3	0.0049	0.98	0.4241
T*D	6	0.0148	1.49	0.2405
P*D	3	0.0036	0.73	0.5455

* See definitions given in the linear model.

Table 10
Test of Hypotheses

Source	Degrees of Freedom	Sum of Squares	F Value	Pr > F
Treatment	2	.0453	5.32	.158

Table 11
Adjusted Means After Recompaction

Treatment	Number of Observations	Adjusted Means (g/cm^3)	Standard Error (g/cm^3)
Baseline	8	1.50	.04
Pecan	16	1.43	.02
Walnut	16	1.57	.03

Table 12 provides results of a t-test which was used to determine if the treatments come from similar or dissimilar populations. The null hypotheses states that all treatments are from the same population. The difference in mean values obtained for the baseline and pecan treatment will be the same or exceeded approximately 20.3% of the time by chance, assuming both treatments

are from the same population. Likewise, the difference in mean values obtained for the baseline and walnut treatment will be the same or exceeded approximately 21.1% of the time by chance. Also, the difference in mean values obtained for the pecan and walnut treatment will be the same or exceeded approximately 1.0% of time by chance. Since the difference of pecan and walnut values is the greatest (.14 g/cm^3) and the probability of equaling or exceeding this value is very small ($p < .01$), it was determined that the pecan and walnut treatments were not from the same population. The null hypotheses for the other two combinations of treatments was accepted.

Table 12
T-Test for Population Differences

Treatment Differences	Absolute Density Differences g/cm^3	Probability of Equaling or Exceeding the Difference
Baseline-Pecan	.07	.203
Baseline-Walnut	.07	.211
Walnut-Pecan	.14	.009

The ability of the experiment to detect small differences between the treatments was limited. It appears that the pecan shells may have a positive effect on the density of the recompacted soil, but the statistical analysis was unable to confirm this suspicion. The walnut shell treatment does not appear to have any impact on preventing recompaction. In fact, the results show that the addition of walnut shells may, if anything, increase the recompacted soil density.

Nuclear Gage Readings Versus Gravimetric Sampling. A comparison of the nuclear gage readings and the gravimetric measurements was made. After the nuclear gage readings were taken, the gage was relocated outside the ripped zone and additional readings were taken. Then a core sample was extracted midway between the nuclear gage probe locations. Three samples were taken measuring approximately 10.2 cm (4.0 in.) long and were centered at 10.2 cm (4.0 in.), 22.9 cm (9.0 in.) and 38.1 cm (15.0 in.) below the surface of the soil. For the purposes of this study, the two most shallow samples were analyzed (i.e., compared to the nuclear density readings). The mean of the nuclear gage readings ranged from 2.1 % to 2.4 % below that of the mean of the gravimetric core samples. This indicates on the average, the nuclear gage provides reliable estimates of soil bulk density. One possible reason for the disagreement between the two methods is the potential for compaction during gravimetric sampling. This was likely to occur due to the type of coring tube chosen. In addition, the compaction of the soil during the preparation of the access holes may have increased the density between the probes. Also, it is recognized that the soil density outside of the ripped zone was measured with the nuclear gage, especially at depths of 20.3 - 25.4 cm (8 and 10 in.) below the soil surface. This may have increased the density readings since lateral failure and subsequent compaction due to tillage is likely to occur in this zone. Due to this reasons, both the nuclear gage readings and the gravimetric measurements may be higher than true densities.

Mechanical Resistance. Resistance to penetration was measured in the ripped zone, excluding the path of the ripper. The resistance in the ripping path was very low and caused the cone shaft to veer substantially. This affects the resistance readings. Since the location of the injected material,

other than within the path, was unknown prior to sampling, quite often the cone penetrometer did not pierce the thin layer of injected material. Consequently, this method of measuring soil compaction was found to be unacceptable to measure the effect of treatment in the material injected zone. The penetrometer readings are shown in Tables 31 through 36 for each trial to document the experiment performed. In a few cases the cone penetrometer broke through to adjacent holes. This caused low, erratic readings and is the reason for the missing values.

Table 37 in the Appendix shows a summary of the initially compacted resistance readings. Both the pecan and walnut treatments have lower resistance readings when compared to the baseline treatment. This is inconsistent with both the nuclear gage and gravimetric bulk density data. Generally, bulk density and mechanical resistance are positively correlated (Barnhisel, 1988).

Table 38 in the Appendix shows a summary of those readings that pierced injected material in the recompacted stage. One reading was taken in the material injected zone for the walnut treatment. Comparing the baseline and the pecan treatments, the top interval shows similar resistance readings. The middle interval shows the pecan with lower resistance readings as compared to the baseline.

Gravimetric Bulk Density and Hydraulic Conductivity. Since selected soil core samples that were extracted for gravimetric bulk density were retained for determining hydraulic conductivity, both will be discussed together.

These two methods of sampling are destructive (i.e., the sample was destroyed due to the process of obtaining the measurement). Unlike the nuclear gage readings, the same physical location could not be measured with each successive stage of soil manipulation.

After the measurements were taken, the samples were diced to examine for injected material. As before, many of these samples did not measure the effect of treatment application due to its physical location. Those samples that were found to have material injected are discussed below.

The nature of the deposited material was important. In most cases, it appeared that the coring tube extracted a sample located very close to the path of the ripper. In these cases, the material found in the sample may have been taken from the path of the ripper or from a short finger of material that projected from the path. As a result, quite often only a small part of the cross sectional area contained injected material. A few cases were noted where the material covered the entire cross sectional area. However, it was likely that these samples were taken from the boundary between the ripped zone and the undisturbed volume as shown in Figure 19. When testing a sample for hydraulic conductivity, an increase may be found in that part of the sample that is loosened. However, the conductivity is likely to be reduced over the remainder of the sample that is taken from the unripped area as shown in Figure 19. The measurement taken from such a sample may not represent the ripped zone and the effect of the treatment.

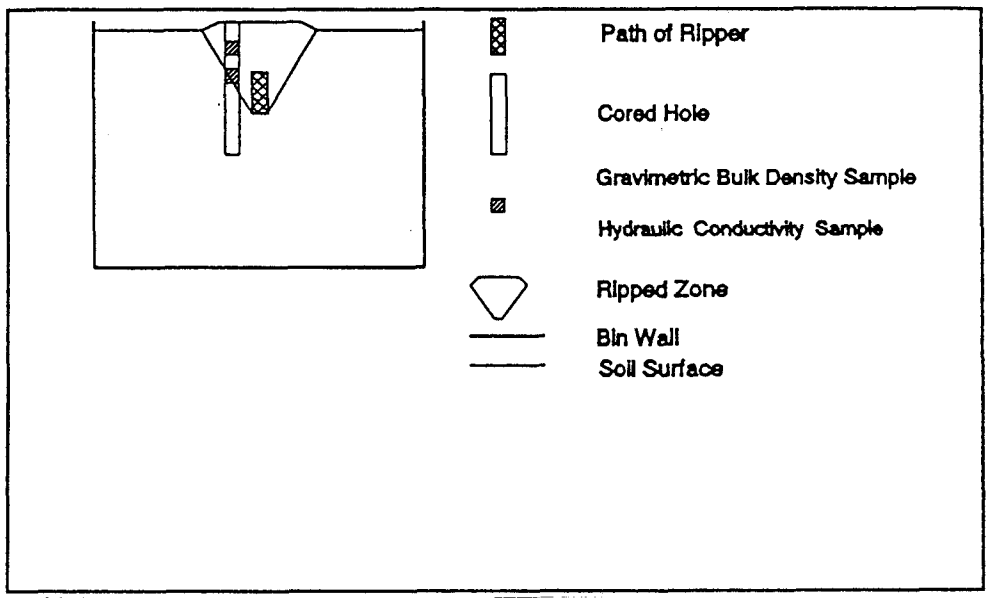


Figure 18 - Cross Section of Gravimetric Bulk Density and Hydraulic Conductivity Sampling Location

Gravimetric Bulk Density. Tables 39 through 48 show the density values for each successive trial to document the experiment performed. Tables 49 through 51 show a comparison of the walnut, pecan, and baseline treatments for each stage of soil manipulation. Those samples in which injected material were found were summarized in Tables 50 and 51. The ranked order of the density values were walnut, pecan, and baseline as shown in Table 49 for the initially compacted values. This was consistent with the nuclear gage data. In the recompacted stage, Table 51, the values were quite close, and did not correspond with the ranked order of the nuclear gage adjusted means.

Hydraulic Conductivity. Tables 52 through 56 show hydraulic conductivity values for each trial. Since a small number of material injected samples were collected, the walnut and pecan treatments were combined to contrast with the baseline treatment. Table 57 shows the initially compacted values for hydraulic conductivity for all three treatments. Tables 58 and 59 show the hydraulic conductivity values for the material injected samples for the ripped and recompacted stages, respectively.

Generally, the hydraulic conductivity values were variable between the treatments, even for the initially compacted stage. Also, the standard deviations were high, possibly due to the limited number of samples collected.

The same physical sample was measured for bulk density and hydraulic conductivity. Generally, bulk density and hydraulic conductivity are negatively correlated (Barnhisel, 1988). As bulk density increases, pore space decreases. Generally, the decrease in pore space causes hydraulic conductivity to decrease. When plotting the gravimetric bulk density values against the hydraulic conductivity values in the initially compacted stage, an unexpected positive correlation was found. One possible explanation involves the reliability of either the gravimetric bulk density values, or the hydraulic conductivity values, or both. The expected negative correlation was found when plotting the values in the recompacted stage. However, a limited number of samples, four in this

case, precludes an accurate picture of the recompacted data. Due to confinement of the bin, additional samples were not possible.

CHAPTER VI

PROTOTYPE SOIL INJECTION SYSTEM

Introduction

The purpose of injection is to place innocuous organic material into the soil during the process of deep tillage for the purpose of preventing recompaction of the soil after tillage. In addition to its role as a soil lightener, as this material decomposes, it is conjectured that it will allow for the passage of air and water to plant roots, which should lead to improved soil structure. Decomposing organic matter may also contribute nutrients to growing plants. It may be noted also that this system could be used to place farm or other benign organic wastes into a soil for the purpose of disposal.

The laboratory experimental system, with its closed and pressurized container, used a non-continuous system of delivery of soil amendment. The objective of this portion of the study is to give initial shape to the plans for a prototype field injection system. It is desired to have a system that is rugged, will deliver most types of organic waste without plugging, and that will have a capacity consistent with field size and loading rates. Some of the ideas that are presented here have been used to guide discussions with manufacturers; equally, these discussions have led to improvements in the plan.

For planning purposes, it is presumed that a maximum of 10 pounds of material is to be injected per foot of travel of a 48-inch ripper tooth. Spacing is assumed to be 48 inches as well so that each pass would affect a 4-ft by 4-ft cross section. The 10 lbs per foot number is based on the experimental injection rates that were achieved in the laboratory, 0.5 to 4.5 lbs per foot for a 12-inch tooth, and also on a calculation of material placed per acre. At ten pounds per foot, each acre would receive 54.5 tons of material. While maximum injection rates are not known, this total would test that bound. Inasmuch as voids -- a volume -- are being filled, the mass, measured as a weight, of material injected will become less with any reduction in specific gravity. Consequently, dry material may be preferable to wet.

Experience with existing subsoilers that are 48 inches deep suggest that track-type tractors similar to a Caterpillar D9 or larger will be needed to draw the injection system. Speeds for these tractors (D9, D10, D11), when in first gear, range from 0 to 2.5 miles per hour with draw-bar pull decreasing inversely from the maximum available to zero at the top speed. Consequently, planning will be based on an average speed of one mile per hour.

Basic Components

There are four principal components within the injection system: (1) hopper/material storage bin, (2) feeder, (3) compressor, (4) injector/subsoiler. Design questions include sizing sufficient for the task, ruggedness and mechanical simplicity, and location on the tractor or on a separate wagon. Some of these questions can be answered in advance and some, such as ruggedness and design simplicity will be deferred until or when a prototype is built.

Power for some of the moving parts of this system will need to come from the tractor. It is presumed that a power take-off will drive an hydraulic pump that in turn will drive feeders and augers. The blower may require a separate motor.

The least-capacity component will determine the maximum output of the system. Whether a feeder or a valve or whatever, all components will need to have the same throughput. Should that productivity be less than desired because of non-availability of larger components then system speed or output or both will have to be reduced.

To avoid immediate recompaction, it is suggested that the material handling system be located between the tractor and the subsoiler. This implies either (1) a train of tractor, wagon to carry the material handling system, and subsoiler or (2) constructing the handling system on the frame of the subsoiler itself. For field flexibility, the total length of the system should be kept as short as possible.

Material Hopper. The design criteria for the hopper are size, delivery system, and material reduction (chopping) system. In addition, consideration is given to hopper location and method of filling it.

The hopper should be as large as possible so as to minimize refilling frequency. However, too large of a hopper will be unwieldy and unable to be filled from mobile haulage units. At ten pounds per foot, one ton will be expended in 200 feet, which is slightly less than one side of a square acre. From the standpoint of reloading, the hopper should not be less than one-ton capacity. If the waste product is loose, already chopped or otherwise unconsolidated, the hopper can be a trough with a chain-conveyor or auger feeder in the bottom. Such hoppers, similar to feed trucks or to ANFO powder trucks, can be ten tons in capacity or more. If the waste product is consolidated, for example round straw bales, then the hopper will need to be shaped so as to receive the product efficiently. An example of this is the round bale feeder, manufactured by Farmhand, which is also round and has a chopper built in.

Feeder. A delivery system will be needed to take material from the bottom of the hopper to the size reducer and then from the reducer to the pressurization system. At maximum capacity (ten pounds per foot and one mile per hour), the system will need to deliver 880 lbs per minute. As mentioned, a mechanical feeder will take material from the bottom of the hopper to the size reducer. If the reducer sits on top of the pressurization chamber, then it in turn will be fed by gravity.

Because of their ready availability and their ability to elevate material, it is suggested that an auger be tried as the mechanical feeder in the first instance. It is conceivable that a chopping blade could be fitted to the end of the auger so as to create a compact and enclosed size reducer.

Pressurization System. Injection will require the waste material to be fed into a pressurized stream of air at the design rate of 880 lbs per minute. In low-capacity systems, solids can be introduced directly into the air stream at the throat of a Bernoulli valve. A restriction in the air stream leaves a negative-pressure (Bernoulli effect) zone at walls of the tube just beyond the restriction. If material is introduced into this negative-pressure zone, it will be picked up by the flowing air stream. Higher capacity systems require some form of air lock such as a rotating star valve to get material into the air stream.

In either case, a blower is needed to provide the air stream. At ten pounds per foot or 880 pounds per minute, approximately 16 cubic feet of material will need to be delivered per minute. If the air stream were ten percent solids by volume, the compressor would need to deliver 160 cfm.

It is presumed that the blower and inlet valve will be directly under the end of the auger and will feed into a short length of flexible reinforced hose that will go directly to the ripper shank. To reduce the advent of hose failure from particle abrasion all curves will be as large a radius as possible. If possible, curves will be built from high-abrasion resistance material. For safety sake, an outer covering should be provided to protect equipment operators from hose failures.

Subsoiler. Existing subsoiling technology can be adapted to the air injection system. It is proposed to use a curved shank with a winged foot of dimensions that have been seen to be effective in other deep tillage trials. The injection tube will go down the back of the shank where it will be protected from abrasion. If possible, it will be divided into two branches with each branch leading to an exit on the trailing edge of each wing. It is hoped that this division of the flow path will encourage more material into the crescent failure zone and less into the slot cut by the shank. The laboratory tests described earlier show clearly that some material can be expected into the crescent zone. However, they also showed that, without special arrangements, most of the injected material will end up in the vertical slot.

To reduce internal friction and the chance of material build-up, all tube joints will be internally flush. It is expected that a tube in the order of two inches diameter will deliver the material to the foot. Each branch within the foot should have half the cross-sectional area of the main tube; this means that exit diameters would be 1.414 in.

In the first instance, tubes will be attached to the back of the ripper shank and foot. Should first trials indicate the possibility of success, designs will be created for incorporating the tube within the shank and the foot.

Contacts with Equipment Manufacturers

The results of the direct contact with equipment manufacturers has been mixed at best. Two general approaches were used in an effort to evaluate the interest of manufacturers in participating in further development of the concepts presented here. The first approach was a general mailing to known manufacturers of deep tillage equipment. The mailing included background on the project and a summary of the project findings. To date only one manufacturer has responded to this iniative and this response expressed no interest in further development.

The second approach has been to endeavor to arrange presentations to manufacturers who were targeted as those that may have greatest interest in the work. A preliminary presentation was made to the local Caterpillar representative in Louisville, Kentucky. This was scheduled as a preface to visiting Caterpillar headquarters in Peoria, Illinois. In fact, the arrangements for such a meeting are still progressing slowly due to Caterpillar's strict requirements surrounding disclosure of intellectual property. A presentation was made to the vice president of engineering and the vice president/international group of Mark Till Corporation in Cedartown, Georgia, the makers of home agricultural equipment. Although this led to an interesting discussion, the representatives of the company stated that they believed the market for such a device to be too small to warrant any development effort on their part. Others such as DMI, Inc. in Peoria, Illinois, and Farmhand, Inc. in Excelsior, Minnesota, have been contacted by telephone. However, no invitations to make presentations were forthcoming.

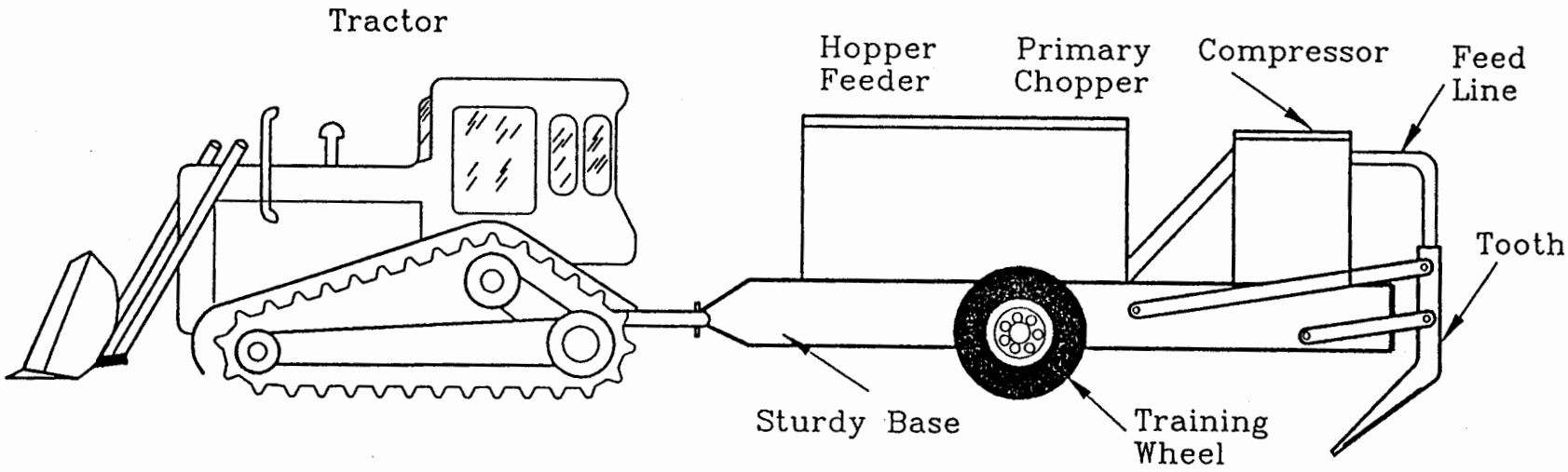


Figure 18a - Conceptual drawing of complete ripping and material injection system

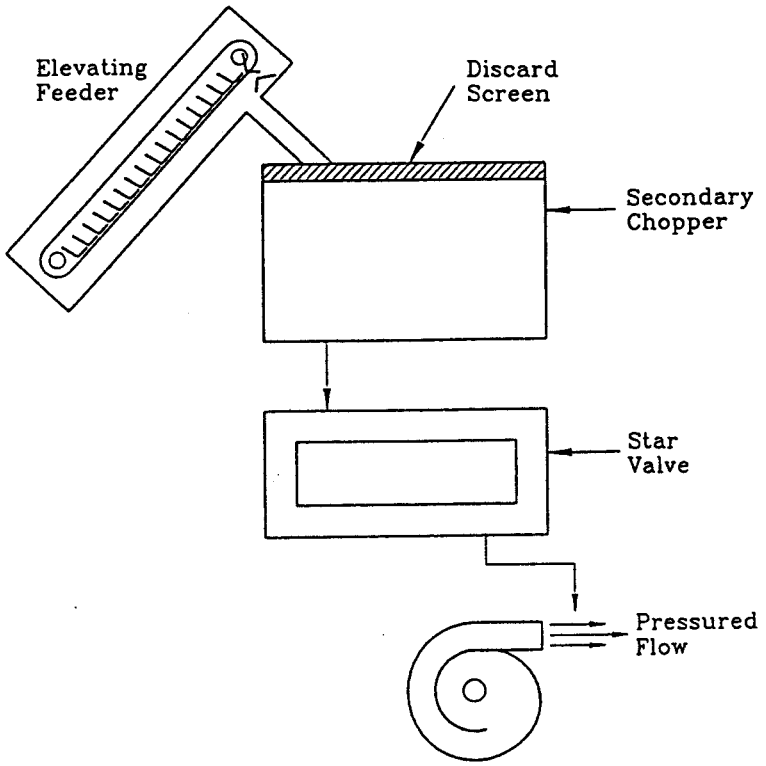


Figure 18b - Schematic diagram of feeder system for pneumatic entrainment of organic material

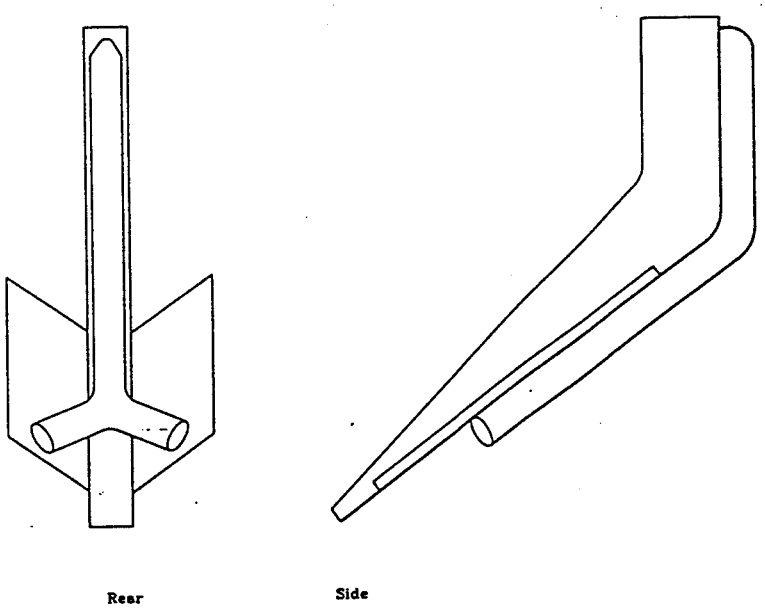


Figure 18c - Detail of ripper shank with air injection nozzle

CHAPTER VII

SUGGESTIONS FOR ADDITIONAL RESEARCH

Verification Trials for Prototype Injection System

When a prototype injection system is built, it will be necessary to run a series of organized trials to (1) test the system, (2) verify the production rates that were assumed for the design, and (3) optimize the design of the subsoiler and its injection ports. While much of the system can be tested in the fabrication shop, the actual deposition of material can be tested only in field trials. Recognizing that there would be any number of frustrations associated with inaugurating a new system, the tests recommended here are for a working prototype that has had the initial faults worked out.

Field trials will be needed merely to determine methods of refilling the hopper while in motion. As these trials are underway, it will be possible to measure deposition rates and compare them with the design capacity. If less than the design rate is found, it will be necessary to diagnose the constraint: machinery or subsoiler-soil interface. An appropriate step will be to dig out a portion of the disturbed zone to see clearly the distribution of the injected material.

Each trial, therefore, should monitor continuously speed of the tractor and feed rates through the injector. Delays and their causes should be noted. Confirming measurements should be taken such as length of ripped zone and total amount of material injected. Additionally, turn times at the end of a row should be measured and time to refill the hopper should be measured.

Subsoiler

The maximum amount of material that theoretically may be deposited into the ripped zone is dependent upon the size of void that is created. Any disturbance to the soil will provide a dilatant effect, which is an increase in void ratio in the soil. Injection, however, will occur only in the macro-voids that are on the failure surface derived from the cutting shoe. It is presumed that these macro-voids are dependent upon the geometry of the subsoiler. While the size of the overall disturbed zone is a function of depth of cutting, the macro-voids are a function of the shape of the cutting foot.

Many different shapes have been tried in tests of deep tillage machines. However, no tests are known where the intent was to increase the size of void at the base of the crescent failure zone. Consequently, a suggestion for further research is to try different types of subsoiler feet to see if production rates can be enhanced.

Additionally, the prototype design presumes that two injection ports, one at each wing, would be effective. This presumption needs to be tested; for example, would an horizontal slot be more effective than circular ports? It is also presumed that air will return preferentially through the vertical slot and that, as a consequence, there is no need to inject material into the slot itself for it will fill easily. This presumption, too, needs to be tested. Digging out the fill zone, as suggested above, will reveal where the injected material is going. If it is not reaching the vertical slot, then other port arrangements will be needed.

Material Trials

It is expected that the prototype injection system will have been designed with a particular waste material in mind, most likely chopped straw. Nevertheless, additional materials should be tried to determine the versatility of the design. Field trials would concentrate on disposal rates for some or all of the following materials: silage, corn stalks, food processing wastes, animal wastes, and sterile sewage sludge.

For the sake of developing production characteristics, minimum and maximum disposal rates should be developed for each material. This implies that speed and feed rates should be varied until maxima are established. Inasmuch as zero is an easy and trivial target, a minimum rate implies the least amount that can be delivered while still maintaining an uniform flow.

Recompaction

Some trials should be aimed at creating deliberate recompaction to see if the benefit that was seen in the laboratory tests can be seen in the field as well. This implies ripping some zones with injection and then some without. Both zones would be subject to similar amounts of machinery movement after they were ripped. The Giddings soil probe or the nuclear density gauge would be used to measure the recompacted density.

Crop Yields

Once an effective injection system is available, long-term trials for crop yield should be established. Corn is the crop most sensitive to deep compaction and should, therefore, be planted in, at least, a five-year succession on sufficient test and control plots to assure replication of results. Only normal tillage practice would be performed during the period of the trial.

CHAPTER VIII

CONCLUSIONS

The conclusions and recommendations outlined in this chapter are supported by the results and statistical analysis of the experimental data. The following objectives were addressed in various stages of the experiment:

1) To determine the feasibility of injecting various materials into the voids caused by deep-tillage with the use of air pressure;
2) To determine the effects of material injection on recompaction of a deep-tilled soil; and
3) To provide information for further study.

These objectives were accomplished primarily through the use of a physical, laboratory model. Several bins of soil were prepared, each involving three distinct stages:

1) Initially compacted soil;
2) Deep-tilled soil with material injected simultaneously; and
3) Recompacted soil.

After each stage, the following parameters were measured:

1) Dry bulk density, g/cm^3 (lbs/ft^3);
2) Moisture content, percent by mass;
3) Mechanical resistance, kPa (psi); and
4) Hydraulic conductivity, cm/sec (in./sec).

The first step was to determine the feasibility of injecting various materials into the voids caused by deep-tillage. The workability of the material injection system was demonstrated with each ripping stage of the experiment. Various types of organic and inorganic material were injected into the soil with a sandblaster. This method of material injection was successful with respect to physically placing some material in the soil during ripping.

The primary area of interest shifted during the execution of the experiment as a result of observed injection patterns. Initially, the small voids created outside the ripper path were expected to show some treatment effect. Subsequent visual inspection consistently indicated that the bulk of the inserted material was deposited in the ripper path. This led to the difficulty of maintaining an adequate sampling program. Since the initial sampling scheme was horizontally distributed, it was found that, for these experiments, the best method of measuring compaction and recompaction for deep-tilled soil with injected material was the nuclear gage.

In order to determine the effect that the injected material had on the recompaction of deep-tilled soil, the material injected zone must first be sampled or monitored. Several of the methods used as an indication of compaction and recompaction were not adequately representative of this zone. These methods included gravimetric bulk density, hydraulic conductivity and mechanical resistance. Prior to sampling, the location of the injected material could not be determined. However, based on the excavation of previous trials, it was fairly certain that most of the material was located in the path of the ripper. Bulk density, as measured with the nuclear gage, was the

primary method that was capable of determining the amount of compaction and recompaction occurring across the ripped zone. This is because it also measured variations vertically.

The amount of material injected during each trial varied and may not have been adequate to produce consistent results. The laboratory system of air injection was crude and would require considerable modification if a prototype was developed. Therefore, all of the voids may not have been filled with organic material. Secondly, fracturing may not have been as extensive as desired because the soil was ripped at a fairly high moisture content. The moisture content was kept near the optimum for compaction, but this clearly is not the optimum for ripping. Limited fracturing could have prevented the material from being distributed more evenly throughout the soil. The optimum moisture content for ripping and injection would be a fruitful area for prototype research.

The second step was to determine the effects of material injection on the recompaction of deep-tilled soil. Figure 36 in the Appendix shows that the pecan treatment profile has a larger difference from the initially compacted stage to the recompacted stage, when compared to the walnut and baseline treatments. However, the statistical analysis was unable to confirm that the observation was significant.

There are a number of factors that could have contributed to the inconclusive nature of the statistical results. The first factor that must be considered is the possibility that injection of organic material does not help prevent recompaction. However, the results of the tests using pecan shells would seem to indicate that there is some positive effect. Another possibility is that inadequate amounts of material were injected in some cases to fill all the voids due to limitations of the injection system. This factor is addressed above. Another consideration is that the sampling technique was not adequate to detect the differences after injection and recompaction. This is a real possibility since the particle density of the injected material was fairly close to the particle density of the soil (no less than 67% of soil particle density). However, despite the results of the statistical analysis, the ability to inject material into the soil during the ripping process was demonstrated and observed.

The final objective was to provide information for further study. Due to the limited size of the soil bin, only one treatment could be applied at a time. This design limited the sensitivity of the statistical analysis. Either many small bins of soil or one large bin containing all treatments must be processed in order to maximize sensitivity to treatment differences.

Furthermore, modifications in the basic equipment used in ripping are recommended. The stroke of the hydraulic cylinder limited the length of continuous material injection. It is suggested for future laboratory studies that the cylinder be replaced with one having a longer stroke or an alternate method of driving the ripper be employed.

Additional methods of measuring the effects of the injected material in the path of the ripper may be needed. This may require the use of a different type of injection material. This will also require the development of an injection system to handle cohesive material. Generally, cohesive materials are difficult to convey pneumatically. The noncohesive nut shells used in this experiment may be replaced by cohesive material, which may result in a better core sample taken in or near the path of the ripper.

A potential area of research may focus on the determination of the quantity of material to be injected into the soil that will achieve a maximum benefit. By injecting different amounts of a certain material into the soil and studying how it affects recompaction of the soil, one may possibly

determine the optimum amount of material to be injected in order to reduce or prevent recompaction. This would require the installation of a flow meter in the conveying hose. In addition, a containment system is needed for the material when testing for smooth flow prior to the execution of ripping and to control material that is discharged from the soil bin during ripping. This will allow for a better estimate of the material injected into the soil during ripping.

While laboratory modeling was necessary to demonstrate the principles involved, future field studies are needed to verify the initial work. It would also be desirable to observe the effect of natural seasonal cycles on soil that has been ripped and injected with organic material. Field validation is necessary to support or disprove the conclusions of this experiment.

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APPENDIX

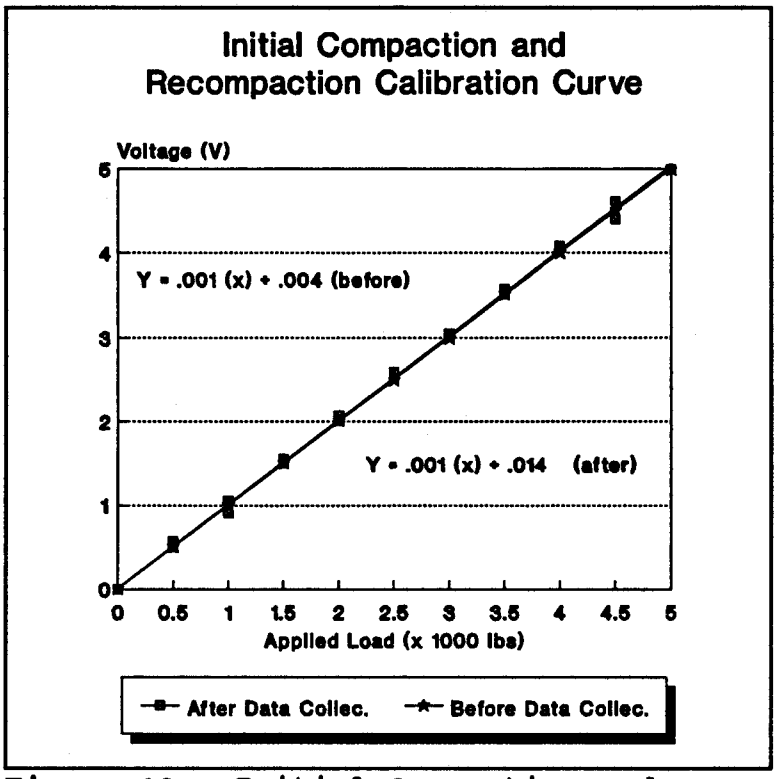

Figure 19 - Initial Compaction and Recompaction Calibration Curve

Table 13
Initial Compaction and Recompaction Calibration Curve

Applied Load (lbs)	Voltage (V)			
	Before		After	
0	0.00	0.00	0.00	0.00
500	0.51	0.50	0.57	0.50
1000	1.01	1.00	1.05	0.90
1500	1.51	1.50	1.55	1.50
2000	2.01	2.01	2.07	2.01
2500	2.50	2.50	2.59	2.52
3000	3.00	2.99	3.05	3.02
3500	3.52	3.51	3.57	3.51
4000	4.00	4.01	4.08	4.05
4500	4.51	4.50	4.61	4.40
5000	4.99		5.00	

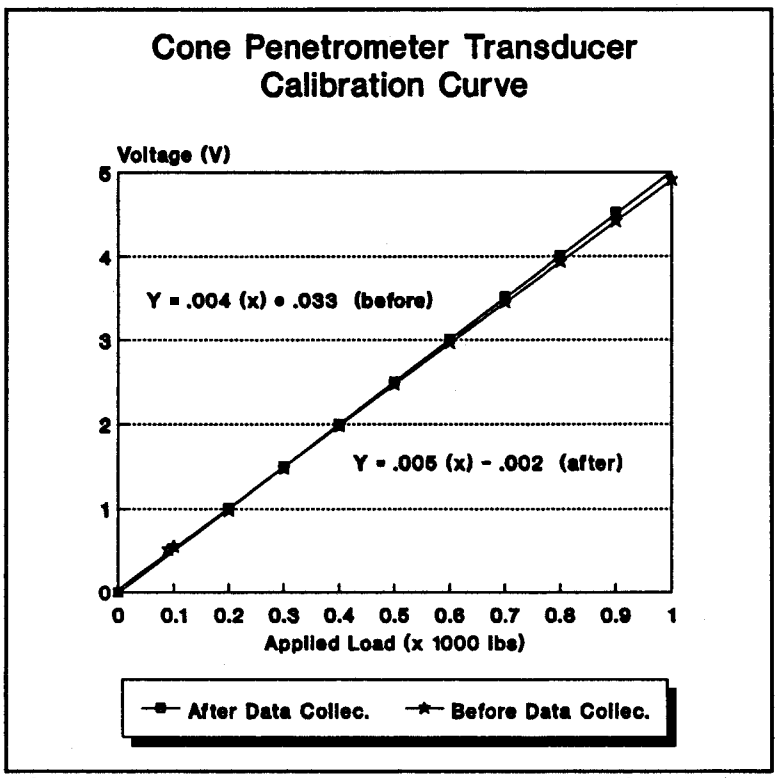

Figure 20 - Cone Penetrometer Calibration Curve

Table 14
Cone Penetrometer Calibration Curve

Applied Load (lbs)	Voltage (V)	
	Before	After
0	0.01	0.00 0.00
90	0.51	
100	0.55	
200	0.98	1.01 1.01
300	1.48	1.49 1.50
400	1.98	1.99 2.00
500	2.47	2.49 2.50
600	2.97	3.01 3.01
700	3.45	3.49 3.52
800	3.94	3.99 4.01
900	4.42	4.50 4.53
1000	4.92	

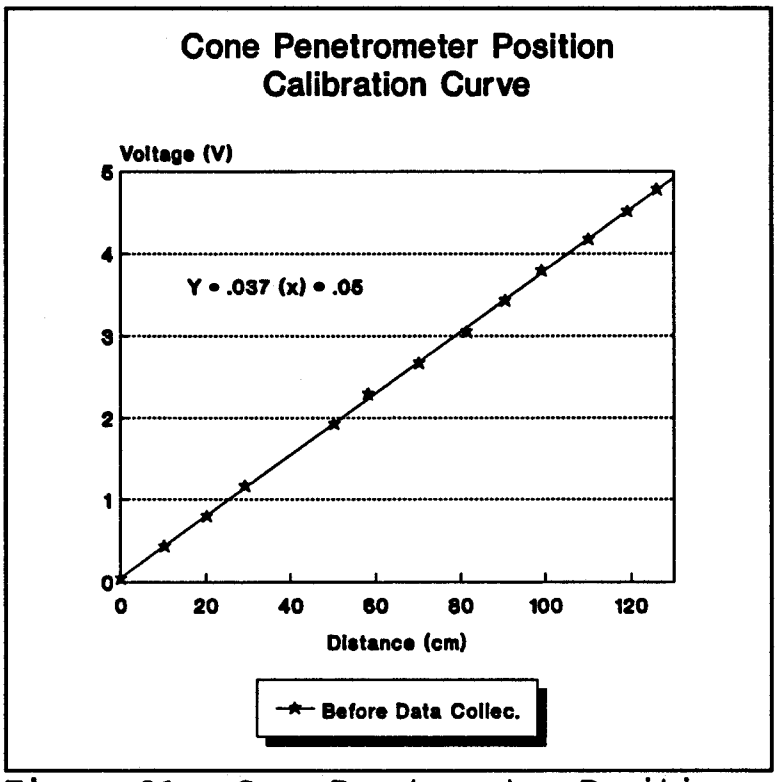

Figure 21 - Cone Penetrometer Position Calibration Curve

Table 15
Cone Penetrometer Position Calibration Curve
Before Data Collection

Distance (cm)	Voltage (V)
0.0	0.04
10.2	0.43
20.2	0.80
29.2	1.17
50.2	1.93
58.2	2.29
70.2	2.67
81.4	3.05
90.4	3.43
99.0	3.79
110.0	4.17
119.1	4.51
126.0	4.78

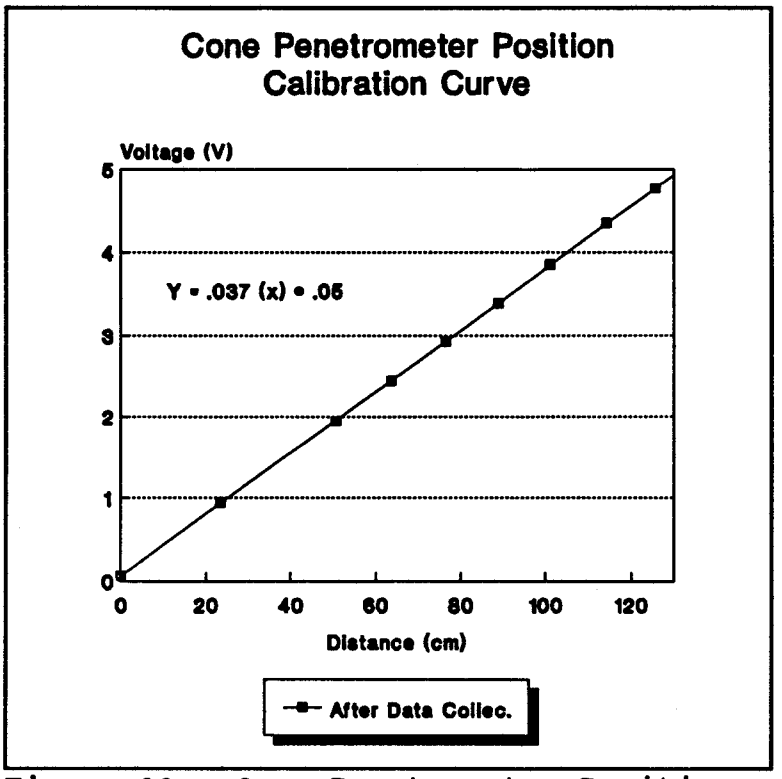

Figure 22 - Cone Penetrometer Position Calibration Curve

Table 16
Cone Penetrometer Position Calibration Curve
After Data Collection

Distance (cm)	Voltage (V)
0.0	0.06
23.5	0.92
50.6	1.95
63.7	2.44
76.5	2.92
88.9	3.39
101.1	3.85
114.3	4.35
125.7	4.77

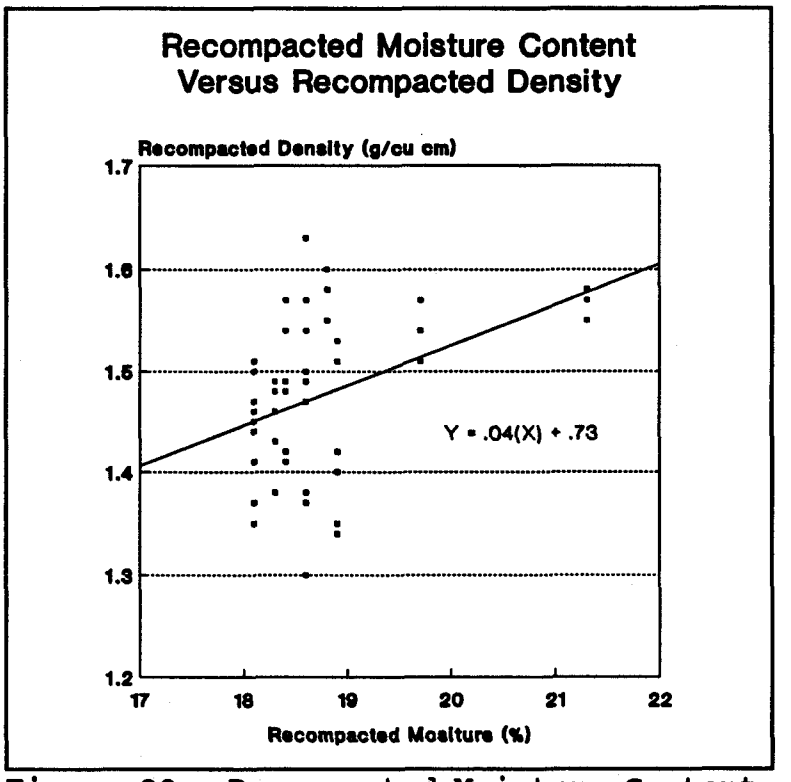

Figure 23 - Recompacted Moisture Content Versus Recompacted

Table 17
Recompacted Density
(g/cm^3)

Trial Number				
B1	S2	S3	S4	S5
1.46	1.55	1.58	1.53	1.47
1.46	1.55	1.57	1.51	1.49
1.47	1.54	1.57	1.49	1.46
1.50	1.63	1.51	1.54	1.47
1.38	1.60	1.55	1.40	1.37
1.43	1.58	1.57	1.34	1.24
1.44	1.57	1.57	1.41	1.35
1.51	1.50	1.54	1.48	1.41
1.49			1.42	1.38
1.48			1.35	1.30
1.46			1.42	1.37
1.51			1.57	1.45

Table 18
Recompacted Moisture Content
(g/cm^3)

Trial Number				
B1	S2	S3	S4	S5
18.3	18.8	21.3	18.9	18.6
18.3	18.8	21.3	18.9	18.6
18.1	18.6	19.7	18.4	18.1
18.1	18.6	19.7	18.4	18.1
18.3	18.8	21.3	18.9	18.6
18.3	18.8	21.3	18.9	18.6
18.1	18.6	19.7	18.4	18.1
18.1	18.6	19.7	18.4	18.1
18.3			18.9	18.6
18.3			18.9	18.6
18.1			18.4	18.1
18.1			18.4	18.1

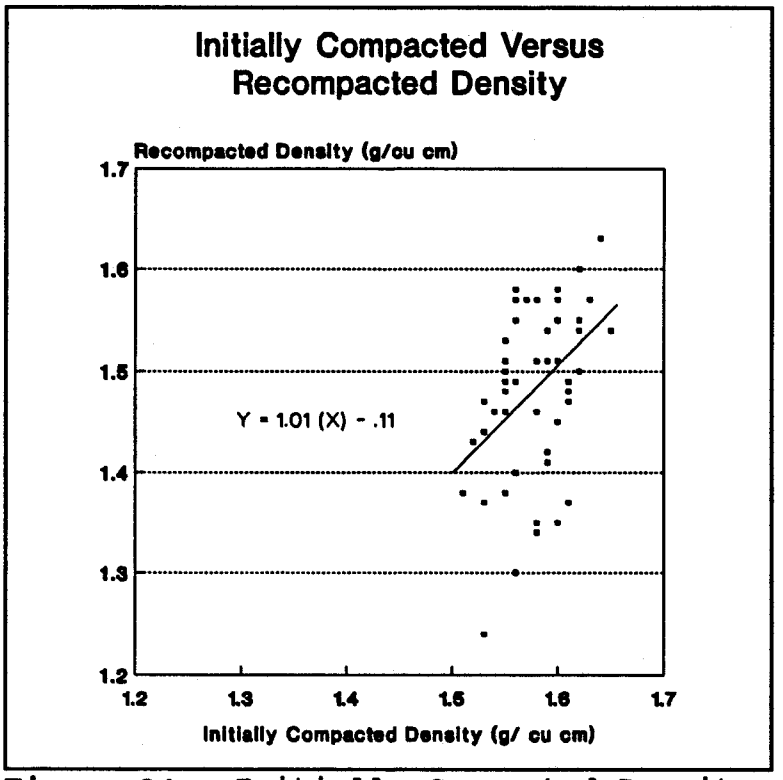

Figure 24 - Initially Compacted Density Versus Recompacted Density

Table 19
Initially Compacted Density
(g/cm^3)

Trial Number				
B1	S2	S3	S4	S5
1.55	1.60	1.56	1.55	1.53
1.54	1.62	1.58	1.59	1.56
1.53	1.65	1.58	1.61	1.58
1.55	1.64	1.60	1.62	1.61
1.51	1.62	1.56	1.56	1.53
1.52	1.60	1.56	1.58	1.53
1.53	1.60	1.57	1.59	1.60
1.55	1.62	1.59	1.61	1.59
1.55			1.59	1.55
1.55			1.58	1.56
1.54			1.59	1.61
1.58			1.63	1.60

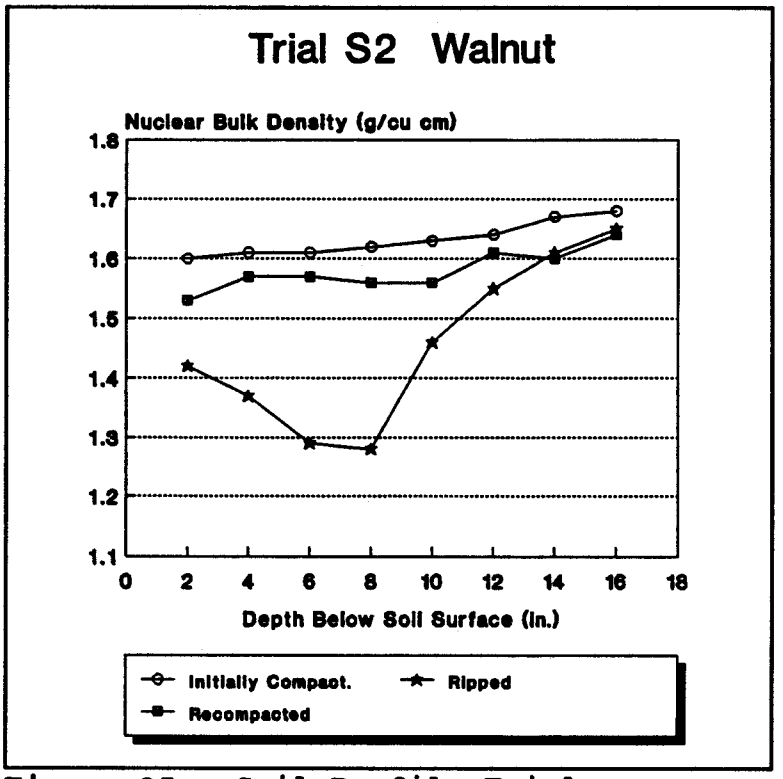

Figure 25 - Soil Profile Trial S2 Walnut

Table 20
Nuclear Bulk Density
Trial S2
g/cm³

Depth Below Surface (in.)	Initially Compacted	Ripped	Recompacted
2	1.60	1.42	1.53
4	1.61	1.37	1.57
6	1.61	1.29	1.57
8	1.62	1.28	1.56
10	1.63	1.46	1.56
12	1.64	1.55	1.61
14	1.67	1.61	1.60
16	1.68	1.65	1.64

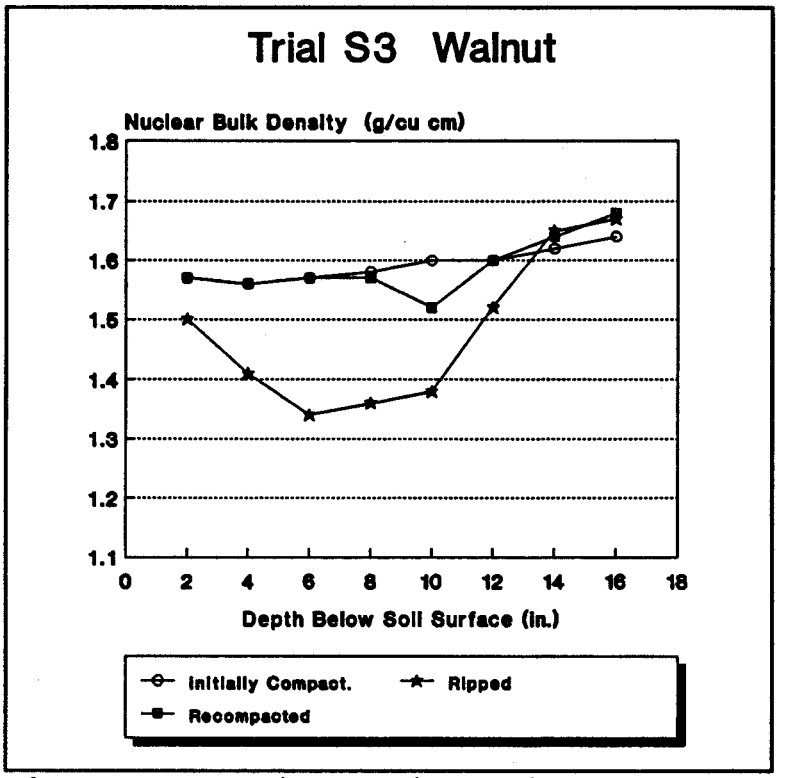

Figure 26 - Soil Profile Trial S3 Walnut

Table 21
Nuclear Bulk Density
Trial S3
g/cm³

Depth Below Surface (in.)	Initially Compacted	Ripped	Recompacted
2	1.57	1.50	1.57
4	1.56	1.41	1.56
6	1.57	1.34	1.57
8	1.58	1.36	1.57
10	1.60	1.38	1.52
12	1.60	1.52	1.60
14	1.62	1.65	1.64
16	1.64	1.67	1.68

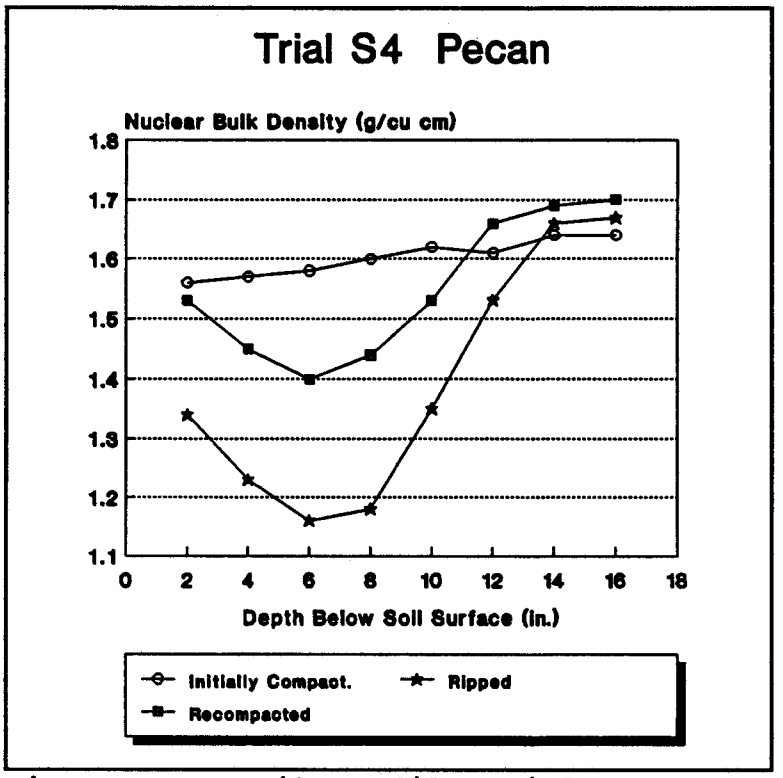

Figure 27 - Soil Profile Trial S4 Pecan

Table 22
Nuclear Bulk Density
Trial S4
g/cm³

Depth Below Surface (in.)	Initially Compacted	Ripped	Recompacted
2	1.56	1.34	1.53
4	1.57	1.23	1.45
6	1.58	1.16	1.40
8	1.60	1.18	1.44
10	1.62	1.35	1.53
12	1.61	1.53	1.66
14	1.64	1.66	1.69
16	1.64	1.67	1.70

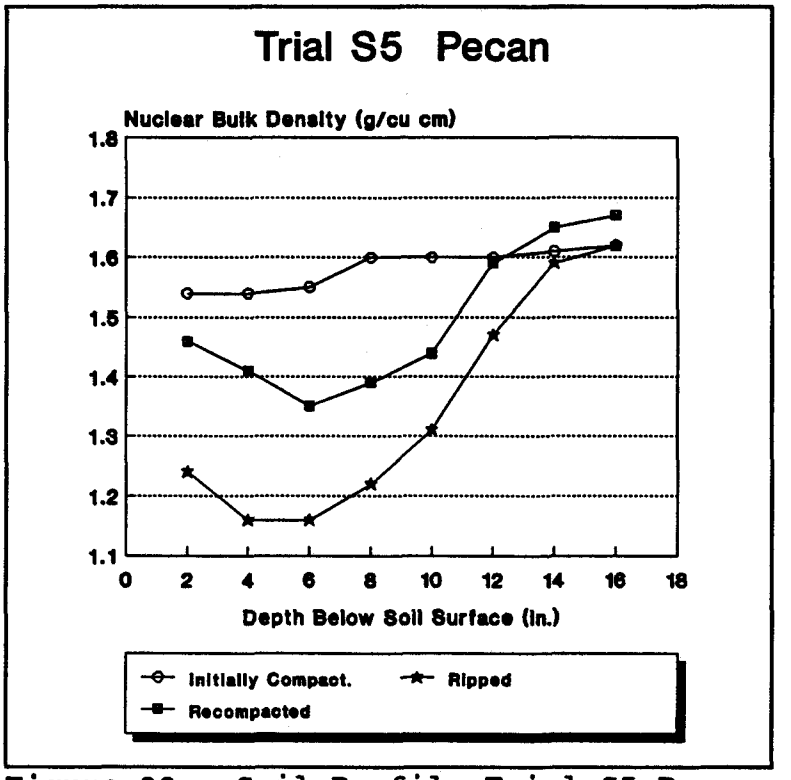

Figure 28 - Soil Profile Trial S5 Pecan

Table 23
Nuclear Bulk Density
Trial S5
g/cm³

Depth Below Surface (in.)	Initially Compacted	Ripped	Recompacted
2	1.54	1.24	1.46
4	1.54	1.16	1.41
6	1.55	1.16	1.35
8	1.60	1.22	1.39
10	1.60	1.31	1.44
12	1.60	1.47	1.59
14	1.61	1.59	1.65
16	1.62	1.62	1.67

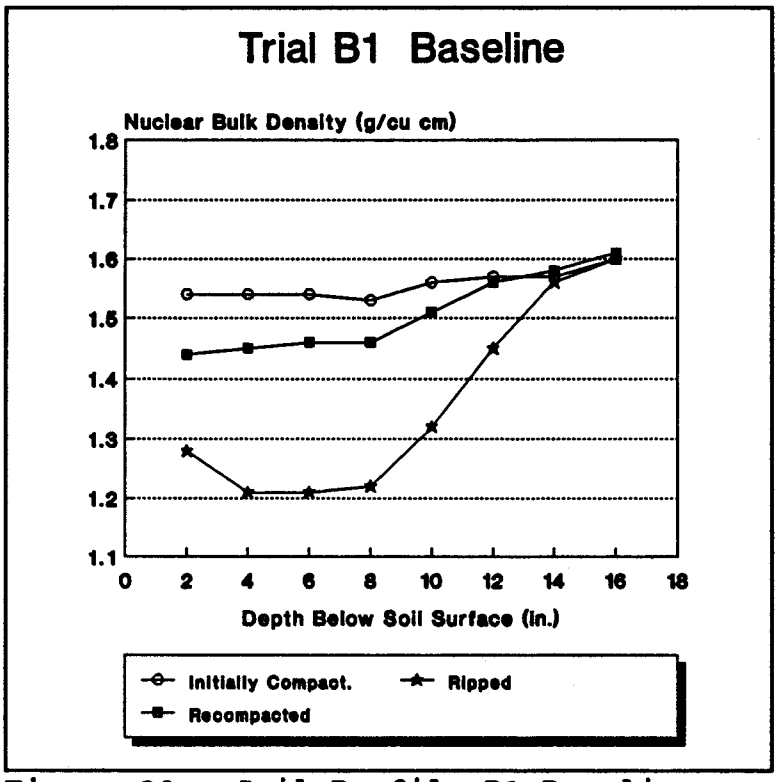

Figure 29 - Soil Profile B1 Baseline

Table 24
Nuclear Bulk Density
Trial B1
g/cm³

Depth Below Surface (in.)	Initially Compacted	Ripped	Recompacted
2	1.54	1.28	1.44
4	1.54	1.21	1.45
6	1.54	1.21	1.46
8	1.53	1.22	1.46
10	1.56	1.32	1.51
12	1.57	1.45	1.56
14	1.57	1.56	1.58
16	1.60	1.60	1.61

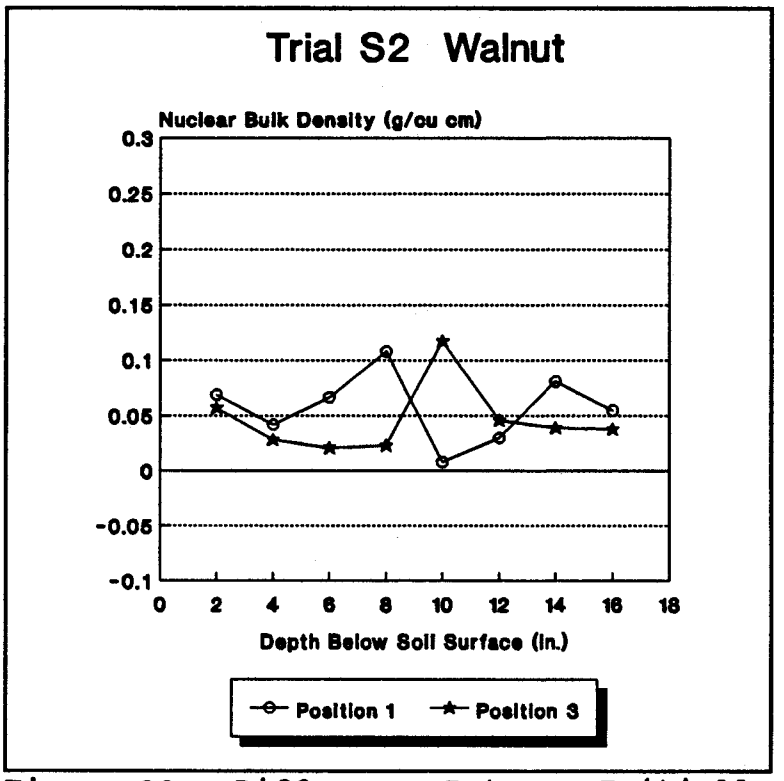

Figure 30 - Difference Between Initially Compacted and Recompacted Density Trial S2

Table 25
Difference Between Initially Compacted
and Recompacted Density
Trial S2
g/cm³

Depth Below Surface (in.)	Position	
	One	Three
2	0.07	0.06
4	0.04	0.03
6	0.07	0.02
8	0.11	0.02
10	0.01	0.12
12	0.03	0.05
14	0.08	0.04
16	0.06	0.04

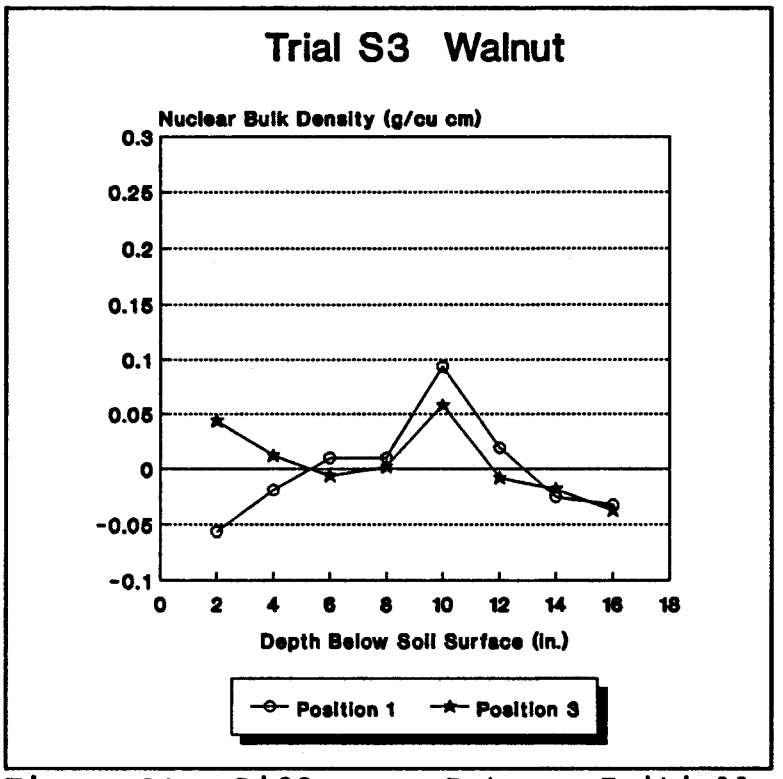

Figure 31 - Difference Between Initially Compacted and Recompacted Density Trial S3

Table 26
Difference Between Initially Compacted
and Recompacted Density
Trial S3
g/cm³

Depth Below Surface (in.)	Position	
	One	Three
2	-0.06	0.04
4	-0.02	0.01
6	0.01	-0.01
8	0.01	0.00
10	0.09	0.06
12	0.02	-0.01
14	-0.02	-0.02
16	-0.03	-0.04

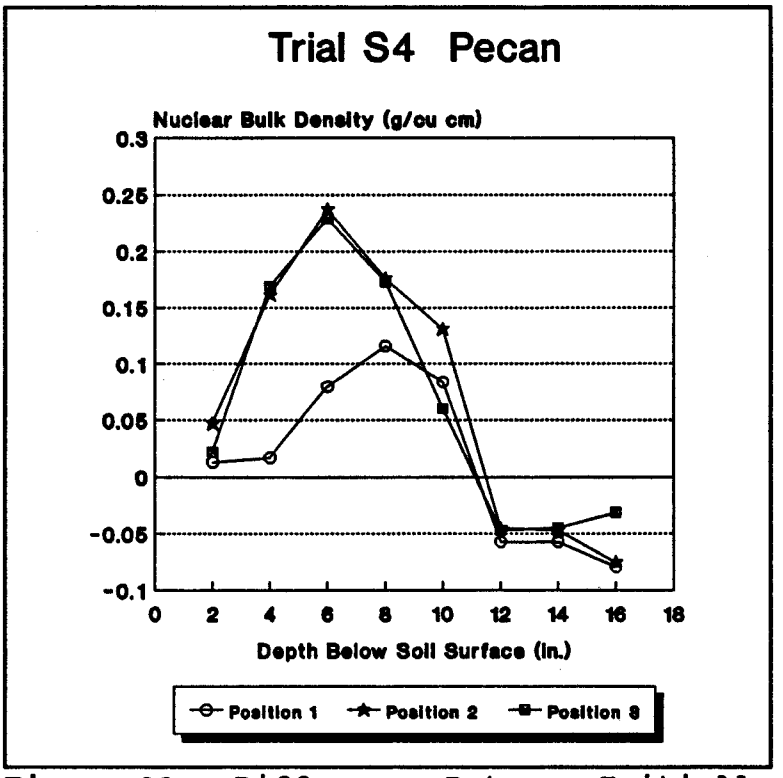

Figure 32 - Difference Between Initially Compacted and Recompacted Density Trial S4

Table 27
Difference Between Initially Compacted
and Recompacted Density
Trial S4
g/cm³

Depth Below Surface (in.)	Position		
	One	Two	Three
2	0.01	0.05	0.02
4	0.02	0.16	0.17
6	0.08	0.24	0.23
8	0.12	0.18	0.17
10	0.08	0.13	0.06
12	-0.06	-0.04	-0.05
14	-0.06	-0.05	-0.04
16	-0.08	-0.08	-0.03

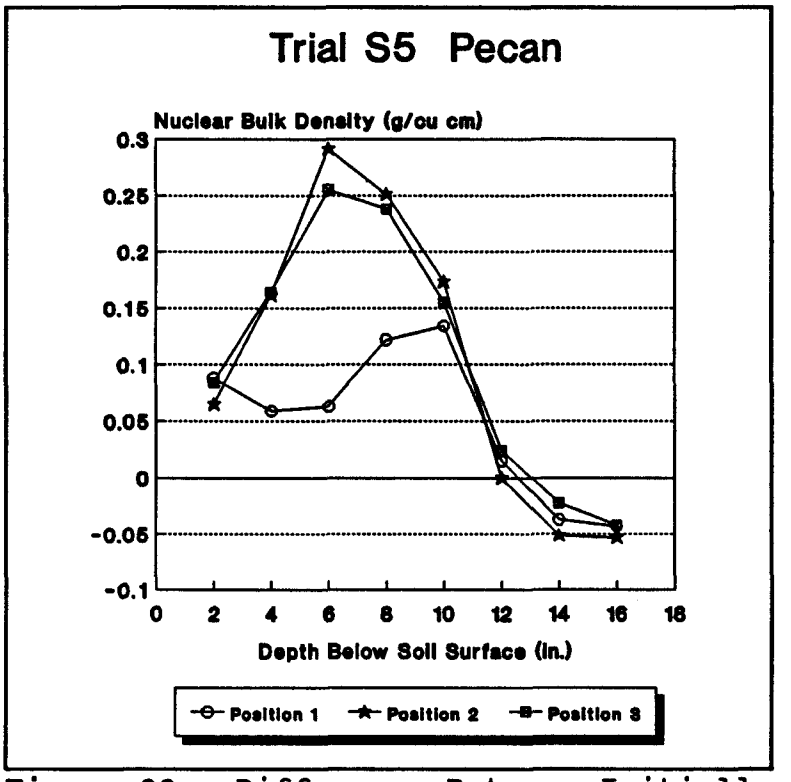

Figure 33 - Difference Between Initially Compacted and Recompacted Density Trial S5

Table 28
Difference Between Initially Compacted
and Recompacted Density
Trial S5
g/cm³

Depth Below Surface (in.)	Position		
	One	Two	Three
2	0.09	0.06	0.08
4	0.06	0.16	0.16
6	0.06	0.29	0.26
8	0.12	0.25	0.24
10	0.13	0.17	0.15
12	0.02	0.00	0.02
14	-0.04	-0.05	-0.02
16	-0.04	-0.05	-0.04

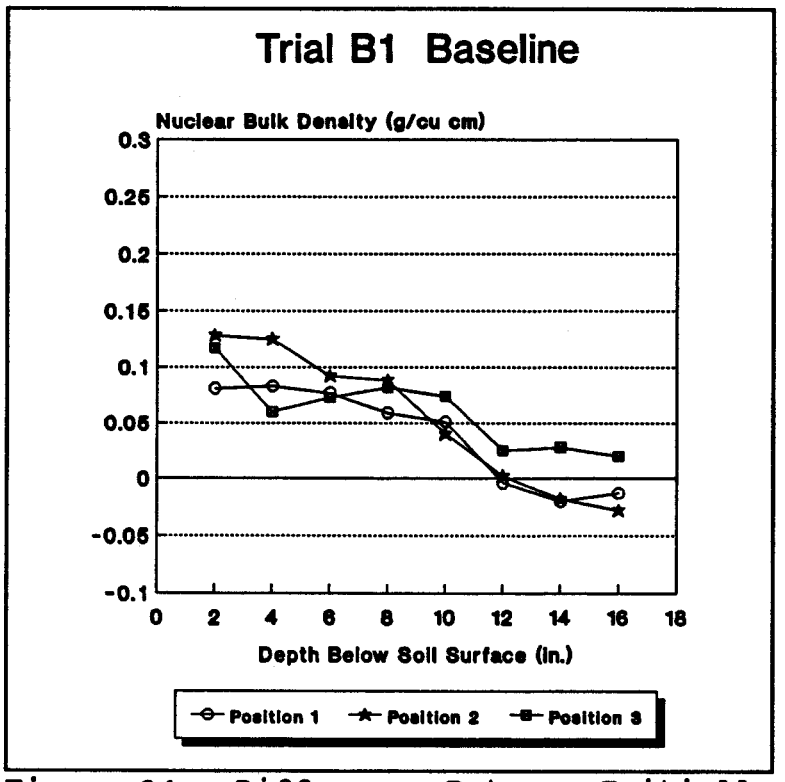

Figure 34 - Difference Between Initially Compacted and Recompacted Density Trial B1

Table 29
Difference Between Initially Compacted
and Recompacted Density
Trial B1
g/cm³

Depth Below Surface (in.)	Position		
	One	Two	Three
2	0.08	0.13	0.12
4	0.08	0.12	0.06
6	0.08	0.09	0.07
8	0.06	0.09	0.08
10	0.05	0.04	0.07
12	0.00	0.00	0.02
14	-0.02	-0.02	0.03
16	-0.01	-0.03	0.02

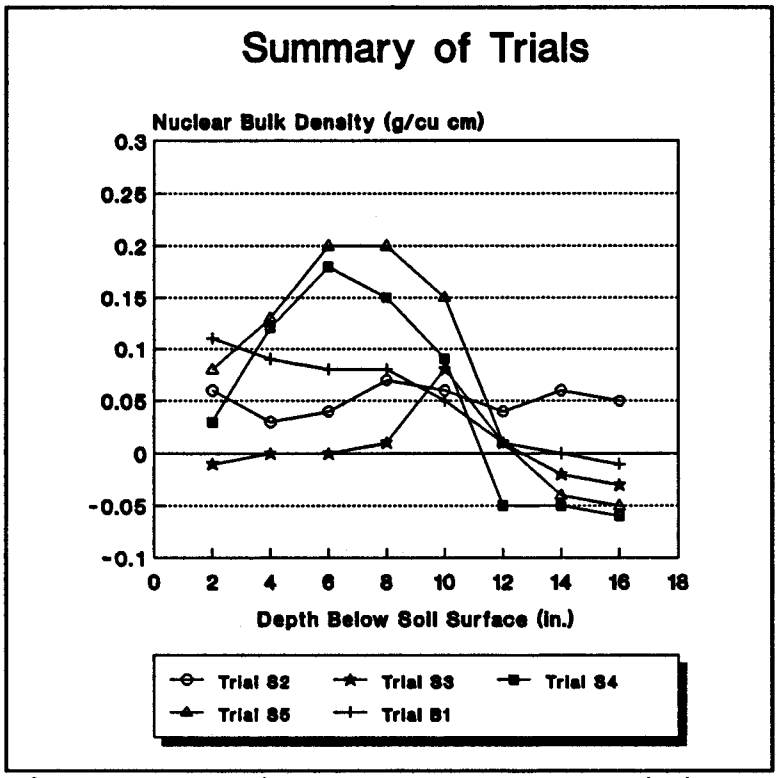

Figure 35 - Difference Between Initially Compacted and Recompacted Density Summary of Trials

Table 30
Difference Between Initially Compacted and Recompacted Density Summary of Trials

Depth Below Surface (in.)	Trial				
	B1	S2	S3	S4	S5
2	0.11	0.06	-0.01	0.03	0.08
4	0.09	0.03	0.0	0.12	0.13
6	0.08	0.04	0.0	0.18	0.20
8	0.08	0.07	0.01	0.15	0.20
10	0.05	0.06	0.08	0.09	0.15
12	0.01	0.04	0.01	-0.05	0.01
14	0.00	0.06	-0.02	-0.05	-0.04
16	-0.01	0.05	-0.03	-0.06	-0.05

Table 31
Trial S1
Mechanical Resistance
(MPa)

Position	Compacted	Ripped	Recompacted
1T	2.25	----	----
1M	3.88	----	----
1B	4.52	----	----
2T	2.80	0.41 F	1.25
2M	4.45	2.87	2.43
2B	4.97	4.38	1.88
3T	2.24	0.48 F	----
3M	4.24	2.63	----
3B	5.62	4.18	----
4T	1.94	2.43	----
4M	3.92	4.08	----
4B	----	4.42	----
5T	----	0.36 F	----
5M	----	0.63 F	----
5B	----	2.99	----

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle readings 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
B = Bottom reading 30.5-45.7 cm (12.0-18.0 in.) below surface, average of continuous data
F = Reading taken in failure zone

Table 32
Trial S2
Mechanical Resistance
(MPa)

Position	Compacted	Ripped	Recompacted
1T	1.01	1.21	1.53
1M	1.41	1.97	2.34
1B	2.38	2.75	3.30
2T	0.69	1.02	1.23
2M	0.99	1.01	1.95
2B	2.56	3.63	4.60
3T	0.81	1.08	1.19
3M	1.24	1.51	2.63
3B	2.32	3.12	3.59
4T	0.74	1.61 F	1.25 F
4M	1.00	1.78 F	2.29 F
4B	2.15	3.62	4.52
5T	0.99	0.51 F	0.77 F
5M	1.56	0.96 F	1.94 F
5B	2.74	2.50	2.70
6T	0.81	0.77 F	1.30 F
6M	1.15	1.43 F	2.25 F
6B	1.97	2.74	3.40
7T	1.26	----	1.11 F
7M	1.54	----	1.96 F
7B	2.79	----	4.07

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle readings 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
B = Bottom reading 30.5-45.7 cm (12.0-18.0 in.) below surface, average of continuous data
F = Reading taken in failure zone

Table 33
Trial S3
Mechanical Resistance
(MPa)

Position	Compacted	Ripped	Recompacted
1T	----	0.44	0.55
1M	----	0.62	0.91
1B	----	1.56	1.64
2T	0.59	0.61	0.74
2M	0.55	0.81	1.08
2B	1.43	1.74	2.15
3T	0.58	0.65	0.92
3M	0.86	0.76	1.33
3B	1.08	1.74	1.56
4T	0.33	0.42	0.66
4M	0.69	1.02	1.29
4B	1.01	1.17	1.89
5T	0.52	0.53 F	0.81 F
5M	0.69	0.83 F	0.93 F
5B	1.41	1.48	1.85
6T	0.50	0.24 F	0.79 F
6M	0.74	0.39 F	0.97 F
6B	1.51	0.97	1.60
7T	0.59	0.35 F	0.68 F,W
7M	0.69	0.49 F	0.84 F,W
7B	1.59	1.68	1.76

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle readings 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
B = Bottom reading 30.5-45.7 cm (12.0-18.0 in.) below surface, average of continuous data
F = Reading taken in failure zone
W = Walnut shells were pierced with cone penetrometer

Table 34
Trial S4
Mechanical Resistance
(MPa)

Position	Compacted	Ripped	Recompacted
1T	0.67	0.76	1.50
1M	0.75	1.02	1.62
1B	1.05	1.19	1.95
2T	0.87	1.19	1.48
2M	0.76	1.21	1.51
2B	1.15	1.44	1.55
3T	0.82	1.06	1.27
3M	1.19	1.43	1.51
3B	1.35	1.41	1.85
4T	0.78	0.98	1.35
4M	0.97	1.33	1.62
4B	1.24	1.68	2.01
5T	0.76	0.20 F	1.04
5M	1.06	0.72 F	1.46
5B	1.24	1.11	1.54
6T	0.83	0.58 F	1.15 F
6M	0.69	1.00 F	1.32 F
6B	1.03	1.22	1.76
7T	0.59	0.49 F	1.07 F,P
7M	0.77	0.88 F	1.21 F,P
7B	0.98	1.34	1.88

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle readings 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
B = Bottom reading 30.5-45.7 cm (12.0-18.0 in.) below surface, average of continuous data
F = Reading taken in failure zone
P = Pecan shells were pierced with cone penetrometer

Table 35
Trial S5
Mechanical Resistance
(MPa)

Position	Compacted	Ripped	Recompacted
1T	0.94	1.08	1.21
1M	1.38	1.56	1.60
1B	1.54	1.74	1.45
2T	0.91	1.14	1.50
2M	1.34	1.40	1.65
2B	1.44	1.47	1.96
3T	0.95	0.97	1.36
3M	1.30	1.47	1.84
3B	1.50	1.87	2.02
4T	1.15	0.44 F,P	1.13 F,P
4M	1.28	0.80 F	1.43 F
4B	1.77	2.01	2.15
5T	1.15	0.40 F	0.97 F,P
5M	1.39	1.30 F	1.75 F,P
5B	1.49	1.74	1.98
6T	1.29	0.28 F	0.86 F
6M	1.47	0.88 F	1.60 F
6B	1.52	1.95	1.81
7T	1.34	0.33 F,P	0.93 F
7M	1.61	1.21 F	1.70 F
7B	1.67	1.75	1.81

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle readings 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
B = Bottom reading 30.5-45.7 cm (12.0-18.0 in.) below surface, average of continuous data
F = Reading taken in failure zone
P = Pecan shells were pierced with cone penetrometer

Table 36
Trial B1
Mechanical Resistance
(MPa)

Position	Compacted	Ripped	Recompacted
1T	0.95	1.17	1.30
1M	1.52	1.48	1.58
1B	1.45	1.59	1.63
2T	1.11	1.39	1.53
2M	1.54	1.77	1.79
2B	1.59	1.92	1.81
3T	1.10	1.23	1.52
3M	1.69	1.64	2.25
3B	1.57	1.49	1.87
4T	1.08	0.35 F	0.87 F
4M	1.44	0.75 F	1.55 F
4B	1.46	1.75	2.12
5T	1.28	0.33 F	0.90 F
5M	1.49	1.16 F	1.42 F
5B	1.68	1.62	2.02
6T	1.24	0.43 F	0.93 F
6M	1.60	1.10 F	1.83 F
6B	1.95	1.15	2.05
7T	1.20	0.38 F	0.54 F
7M	1.64	0.98 F	0.92 F
7B	1.63	1.34	0.25

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle readings 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
B = Bottom reading 30.5-45.7 cm (12.0-18.0 in.) below surface, average of continuous data
F = Reading taken in failure zone

Table 37
Initially Compacted Stage
Mean/Standard Deviation
Mechanical Resistance
(MPa)

Position	Treatment		
	Baseline	Walnut	Pecan
T	1.14/.11	.72/.25	.93/.22
M	1.56/.09	1.01/.34	1.14/.30

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle reading 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data

Table 38
Recompacted Stage
Mean/Standard Deviation
Mechanical Resistance
(MPa)

Position	Treatment		
	Baseline	Walnut	Pecan
T	1.08/.37	.68*	1.06/.08
M	1.62/.41	.84 *	1.46/.27

T = Top reading 0-15.2 cm (0-6.0 in.) below surface, average of continuous data
M = Middle reading 15.2-30.5 cm (6.0-12.0 in.) below surface, average of continuous data
* = One sample

Table 39
Trial 1
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.61	1.56	1.66
1B	----	1.56	1.62
2T	1.53	---	1.66
2B	1.66	---	----
3T	1.56	0.98 F	1.68 F
3B	1.63	1.64	1.70
4T	1.60	1.57	1.62
4B	1.62	1.58	1.59
5T	----	1.52	1.64
5B	1.64	1.50	1.66
6T	1.48	1.46	1.66
6B	1.57	1.53	1.71
7T	1.56	0.73 F	1.64 F
7B	1.62	1.65	1.68
8T	1.56	1.50	1.56
8B	1.58	1.57	1.68

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone

Table 40
Trial 2
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.60	1.69	1.75
1M	----	1.76	1.71
1B	1.68	1.74	1.72
2T	1.61	1.66 F	1.76 F
2M	1.65	1.68 F	1.73 F
2B	1.70	1.72	1.72
3T	1.60	1.66 F	1.73 F
3M	1.69	1.65 F	1.73 F
3B	1.65	1.68	1.68
4T	1.65	1.63 F	1.78
4M	1.70	1.71 F	1.72
4B	1.68	1.70	1.70
5T	1.71	1.62 F	1.73
5M	1.68	1.72 F	1.73
5B	1.71	1.70	1.70
6T	1.73	1.68	1.74 F
6M	1.71	1.67	1.70 F
6B	1.76	1.65	1.70
7T	1.69	1.73	1.77 F
7M	1.70	1.67	1.65 F
7B	1.71	1.74	1.70
8T	1.66	1.73	1.70
8M	1.69	1.74	1.66
8B	1.70	1.67	1.62

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone

Table 41
Trial 3
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.64	1.57	1.74
1M	1.66	1.61	1.72
1B	1.58	1.62	1.76
2T	1.64	1.64 F	1.72 F
2M	1.67	1.64 F	1.70 F
2B	1.66	1.62	1.73
3T	1.63	1.68 F	1.75 F
3M	1.65	1.70 F	1.75 F
3B	1.58	1.69	1.73
4T	1.62	1.62	1.73
4M	1.66	1.68	1.73
4B	1.67	1.67	1.70
5T	1.66	1.56	1.66
5M	----	1.70	1.66
5B	1.62	1.65	1.70
6T	1.55	1.70 F	1.69 F
6M	1.66	1.68 F	1.70 F
6B	1.74	1.73	1.72
7T	1.66	1.66 F	1.66 F
7M	1.67	1.66 F	1.65 F
7B	1.68	1.63	1.64
8T	1.68	1.71	1.66
8M	1.66	1.72	1.65
8B	1.66	1.64	1.64

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone

Table 42
Trial 4
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.66	1.71	1.73
1M	1.67	1.70	1.67
1B	1.71	1.64	1.69
2T	1.70	1.70 F	1.63 F
2M	1.62	1.70	1.73
2B	1.67	1.68	1.73
3T	1.60	1.66 F	1.67 F
3M	1.67	1.71	1.72
3B	1.62	1.73	1.71
4T	1.68	1.70	1.69
4M	1.64	1.72	1.68
4B	1.70	1.70	1.68
5T	1.69	1.67	1.67
5M	1.72	1.73	1.73
5B	1.71	1.68	1.71
6T	1.69	1.73 F	1.69 F
6M	1.75	1.73	1.73
6B	1.72	1.71	1.64
7T	1.75	1.66 F	1.67 F
7M	1.72	1.72	1.69
7B	1.70	1.64	1.70
8T	1.66	1.67	1.72
8M	1.71	1.70	1.72
8B	1.66	1.66	1.70

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone

Table 43
Trial 5
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.67	1.60	1.71
1M	1.56	1.67	1.67
1B	1.62	1.71	1.69
2T	1.68	1.68 F	1.66 F
2M	1.65	1.73	1.64
2B	1.65	1.73	----
3T	1.68	1.35 F	1.67 S,F
3M	1.65	1.69	1.54
3B	1.66	1.74	1.69
4T	1.58	1.64	1.69
4M	1.69	1.63	1.73
4B	1.68	1.72	1.71
5T	1.67	1.66	1.65
5M	1.68	1.71	1.70
5B	1.68	1.69	1.70
6T	1.61	1.57 S,F	1.65 F
6M	1.67	1.71	1.73
6B	1.50	1.73	1.67
7T	1.66	1.33 S,F	1.63 S,F
7M	1.70	1.73	1.72
7B	----	1.69	----
8T	1.68	1.70	1.70
8M	1.70	1.69	1.71
8B	1.71	1.72	1.70

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone
S = Slag product was found in core

Table 44
Trial S2
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.65	1.66	1.65
1M	1.68	1.66	1.67
1B	1.59	1.70	1.70
2T	1.66	1.57 W,F	1.64 F
2M	1.68	1.68	1.70
2B	1.69	1.69	1.70
3T	1.66	1.54 W,F	1.66 W,F
3M	1.68	1.61 W	1.73
3B	1.67	1.68	1.73

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone
W = Walnut shells were found in core

Table 45
Trial S3
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.61	1.65	1.65
1M	1.67	1.70	1.68
1B	1.70	1.71	1.60
2T	1.68	1.63 W,F	1.69 F 1.59 W,F
2M	1.69	1.69 W	1.67 W 1.74 W
2B	1.73	----	1.74 1.71 W
3T	1.70	1.57 W,F	1.69 F 1.66 F
3M	1.71	1.69 W	1.71 1.67 W
3B	1.68	----	1.70 1.71

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone
W = Walnut shells were found in core

Table 46
Trial S4
Gravimetric Bulk Density
(g/cm^3)

Position	Compact-ed	Ripped	Recompacted	
1T	1.63	1.64	1.64	
1M	1.69	1.64	1.68	
1B	1.69	1.69	1.70	
2T	1.63	1.57 F	1.60 F,P	1.64 F,P
2M	1.68	1.67	1.68	1.67
2B	1.68	1.69	1.70	1.71
3T	1.55	1.65 F,P	1.66 F,P	1.64 F
3M	1.65	1.78 P	1.66	1.68
3B	1.66	1.70	1.70	1.68

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone
P = Pecan shells were found in core

Table 47
Trial S5
Gravimetric Bulk Density
(g/cm^3)

Position	Compact-ed	Ripped	Recompacted	
1T	1.61	1.59	1.64	
1M	1.61	1.65	1.64	
1B	1.68	1.68	1.67	
2T	1.64	1.48 F,P	1.54 F,P	1.56 F
2M	1.68	1.64	1.65	1.62
2B	1.65	1.68	1.65	1.69
3T	1.58	1.59 F	1.60 F,P	1.63 F
3M	1.60	1.66	1.64	1.66 P*
3B	1.67	1.63	1.65	1.67

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone
P = Pecan shells were found in core
* = Sample taken in path of ripper

Table 48
Trial B1
Gravimetric Bulk Density
(g/cm^3)

Position	Compacted	Ripped	Recompacted
1T	1.60	1.61	1.64
1M	1.51	1.65	1.64
1B	1.61	1.64	1.63
2T	1.61	1.48 F	1.60 F, 1.66 F 1.66
2M	1.64	1.67	1.64
2B	1.67	----	1.68 1.69
3T	1.65	1.54 F	1.61 F, 1.57 F
3M	1.56	1.63	1.67 1.65
3B	1.66	----	1.62 1.69

T = Top sample 0-15.2 cm (0-6.0 in.) below surface, average of duplicates)
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface, average of duplicates)
B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface, average of duplicates)
F = Sample was taken in failure zone

Table 49
Initially Compacted Stage
Gravimetric Bulk Density
Mean/Standard Deviation
(g/cm^3)

Position	Treatment		
	Baseline	Walnut	Pecan
T	1.62/.03	1.66/.03	1.61/.03
M	1.57/.06	1.68/.01	1.65/.04

T = Top samples 0 - 15.2 cm (0 - 6.0 in.)
M = Middle samples 15.2 - 30.5 cm (6.0 - 12.0 in.)

Table 50
Ripped Stage
Gravimetric Bulk Density
Mean/Standard Deviation
(g/cm^3)

Position	Treatment		
	Baseline	Walnut	Pecan
T	1.51/.04	1.58/.04	1.57/.12
M	1.65/.03	1.66/.05	1.78 *

T = Top samples 0 - 15.2 cm (0 - 6.0 in.)
M = Middle samples 15.2 - 30.5 cm (6.0 - 12.0 in.)
* = One sample

Table 51
Recompacted Stage
Gravimetric Bulk Density
(g/cm^3)

Position	Treatment		
	Baseline	Walnut	Pecan
T	1.61/.04	1.62/.05	1.61/.05
M	1.65/.01	1.69/.04	1.66*

T = Top samples 0 - 15.2 cm (0 - 6.0 in.)
M = Middle samples 15.2 - 30.5 cm (6.0 - 12.0 in.)
* = One sample

Table 52
Trial S2
Hydraulic Conductivity
($x10^{-5}$ cm/sec)

Position	Compacted	Ripped	Recompacted
1T	1.7	2.2	3.3
1M	2.0	---	2.7
1B	---	2.6	---
2T	1.9	10.0 W,F	---
2M	1.4	2.7	2.7
2B	---	---	---
3T	0.7	---	1.4 W
3M	0.8	3.5 W	2.5
3B	2.2	2.8	---

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface
W = Walnut shells found in sample
F = Sample taken in failure zone

Table 53
Trial S3
Hydraulic Conductivity
($x10^{-5}$ cm/sec)

Position	Compacted	Ripped	Recompacted
1T	---	2.2	0.4
1M	2.0	5.3	---
1B	1.6	---	---
2T	2.7	---	0.5 F
2M	2.3	---	0.3 F, 0.7 WF
2B	2.7	---	0.5
3T	1.2	---	0.8 WF, 0.3 F
3M	2.3	---	0.7 F
3B	---	---	---

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface
W = Walnut shells found in sample
F = Sample taken in failure zone

Table 54
Trial S4
Hydraulic Conductivity
($x10^{-5}$ cm/sec)

Position	Compacted	Ripped	Recompacted
1T	0.1	---	0.6
1M	0.4	0.4	---
1B	---	---	---
2T	0.4	1.2 F	0.4 PF, 0.8 PF
2M	1.1	---	---
2B	---	---	---
3T	0.7	0.8 F	0.4 PF, 0.6 F ---
3M	0.6	1.2 PF	---
3B	---	---	

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface
P = Pecan shells found in sample
F = Sample taken in failure zone

Table 55
Trial S5
Hydraulic Conductivity
($x10^{-5}$ cm/sec)

Position	Compacted	Ripped	Recompacted
1T	0.7	0.7	0.4
1M	0.9	0.4	0.5
1B	---	0.5	0.6
2T	---	---	0.3 PF, 0.4 F
2M	---	0.4	0.5 0.6
2B	---	0.3	--- 0.4
3T	---	1.4	0.4 PF ---
3M	0.4	---	0.5 0.3 P
3B	0.5	0.3	--- ---

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface
P = Pecan shells found in sample
F = Sample taken in failure zone

Table 56
Trial B1
Hydraulic Conductivity
($x10^{-5}$ cm/sec)

Position	Compacted	Ripped	Recompacted
1T	1.7	3.5	0.9
1M	---	0.5	1.5
1B	2.4	0.4	0.8
2T	1.1	1.9 F	0.6 F 0.5 F
2M	0.8	1.4	0.4 ---
2B	---	---	--- 0.6
3T	0.6	2.4	1.8 F 1.6 F
3M	0.5	0.3	0.6 0.8
3B	0.2	---	--- 1.0

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface B = Bottom sample 30.5-45.7 cm (12.0-18.0 in.) below surface
F = Sample taken in failure zone

Table 57
Initially Compacted Stage
Hydraulic Conductivity
($x10^{-5}$)
Mean/Standard Deviation

Position	Treatment		
	Baseline	Walnut	Pecan
T	1.13/.55	1.64/.75	.47/.29
M	.65/.21	2.0/.37	.68/.31

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface

Table 58
Ripped Stage
Hydraulic Conductivity
($x10^{-5}$ cm/sec)
Mean/Standard Deviation

Position	Treatment	
	Baseline	Walnut and Pecan
T	2.15/.35	10 *
M	.85/.77	2.17/1.38

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface
* = One Sample

Table 59
Recompacted Stage
Hydraulic Conductivity
($x10^{-5}$ cm/sec)
Mean/Standard Deviation

Position	Treatments	
	Baseline	Walnut and Pecan
T	1.13/.67	.76/.41
M	.60/.20	.70 *

T = Top sample 0-15.2 cm (0-6.0 in.) below surface
M = Middle sample 15.2-30.5 cm (6.0-12.0 in.) below surface
* = One Sample

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