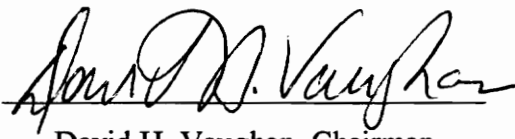


**Cover Crop Residue Effects on Machine-Induced
Soil Compaction**

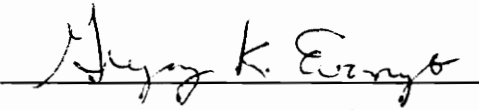
by
Daniel R. Ess

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Agricultural Engineering

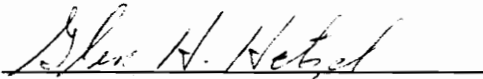
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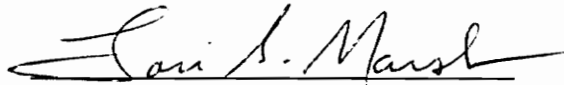
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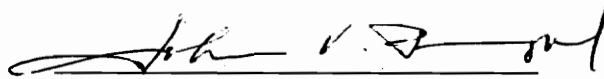
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**Cover Crop Residue Effects on Machine-Induced
Soil Compaction**

by

Daniel R. Ess

David H. Vaughan, Chairman

Agricultural Engineering

(ABSTRACT)

Crop production systems which utilize the biomass produced by rye (*Secale cereale*) to suppress weed growth and conserve soil moisture have been developed at Virginia Tech. The success of alternative, reduced-input crop production systems has encouraged research into the potential for breaking the traffic-tillage cycle associated with conventional tillage crop production systems.

The fragile residues encountered in agricultural crop production, whether incorporated into the soil or distributed on the soil surface, provide minimal protection against compaction by wheeled vehicles. The potential of an intact cover crop to reduce machine-induced effects on soil properties that affect primary crop growth was the subject of this study.

A randomized complete block experiment was conducted at the Whitethorne Farm in Montgomery County, Virginia. One set of plots was arranged on a terrace adjacent to the New River in a fine, mixed, mesic, Aquic Argiudolls. Another set of plots was arranged on an upland site, a river terrace tread, in a fine-loamy, mixed, mesic, Typic Hapludults.

Three rye cover crop treatments were examined. In one, a live cover crop was completely undisturbed prior to tracking by a wheel-type tractor. In another, the cover crop was chemically desiccated, and in the third treatment, all above-ground biomass was removed

from plots prior to machine traffic. The treatments permitted investigation of the effects of crop condition on machine-induced soil compaction and the contribution of root reinforcement to the alteration of soil response to machine traffic. A fall-tilled fallow treatment served as an experimental control.

Three levels of traffic were investigated: one pass, three passes, and five passes. Undisturbed soil core samples were analyzed to determine machine-induced effects on dry bulk density, pore size distribution, and saturated hydraulic conductivity.

The treatments affected soil response to machine traffic. The cover crop treatments altered the soil-plant microenvironment, affecting soil parameters that influence compactibility. Soil compaction was attenuated by the reinforcing effect of a network of undisturbed roots within the soil. There was no convincing evidence that above-ground biomass contributed directly to the reduction of machine-induced compaction effects. Soil response to machine traffic was limited to the uppermost 15 cm of the soil profile.

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Introduction

Mechanization, a vital element in the emancipation of mainstream American society from the toil of its agrarian past, has produced mixed blessings for those who till the soil. The machines that contributed to a tenfold increase in agricultural labor productivity in the last eighty years (Goering, 1992) eased the farmer's burden, allowing farms to increase in size, even as much of the rural population migrated to towns and cities. Less than two percent of Americans now live on farms (Hillgren and Klintberg, 1993). As the farm population has diminished, so too has the voice of farm interests in this nation's seat of government. At a time when society at large exhibits little tolerance of either environmental or food quality degradation, farmers are forced to seek alternative, often management-intensive, crop production strategies. Just as the demand for technical assistance on the farm reaches an all-time high, the U.S. Department of Agriculture is driven to retrenchment under pressure from Capitol Hill (Hillgren, 1993). The American farmer is a victim of the unintended consequences of agricultural mechanization.

An unintended consequence of mechanized crop production that is more within the grasp of the farmer to solve is excessive soil compaction. Average tractor weight has increased from 2.7 tons in 1948 to 6.8 tons at present (Cruse and Gupta, 1991). The two-ton pull-type combine of the 1950's has been replaced by the twelve-ton self-propelled model of the 1990's (NAEDA, 1992). In spite of advances in undercarriage technology, modern machines used for crop production can exert high pressures on the soil. The resulting soil

compaction can significantly alter soil characteristics that affect water movement and plant growth. Soil is particularly vulnerable to compaction under the moisture-content and traffic-density conditions that often exist at planting and harvest. Effects of compaction that takes place at planting tend to endure through harvest. Machine-induced compaction carried over from crop establishment, and often exacerbated by harvest operations, is typically ameliorated by tillage. In conventional tillage crop production systems, the traffic-tillage cycle is repeated season after season.

Conservation tillage cropping systems, as designed, reduce the number and intensity of field operations inherent to conventional cropping systems. Conservation tillage maintains a rough soil surface and/or a crop residue presence on and about the soil surface (Allmaras et al., 1991). Crop residues impede soil detachment and transport due to wind or to rainfall impact, thereby reducing soil erosion. The success of conservation tillage in controlling erosion has led to its use as a primary practice for conservation compliance in the 1985 and 1990 Farm Bills (Allmaras et al., 1991; SRDC, 1993).

In spite of the benefits accruing from erosion control, adoption of a conservation cropping system is not without risk. Conservation tillage can alter soil properties that affect crop growth such as temperature and moisture content (NRC, 1989). Soil temperature often dictates the scheduling of spring crop planting operations. Crop residue has been shown to produce soil surface temperatures 5 to 8 °C lower than measured on bare soil (NeSmith

et al., 1987), thereby delaying planting and effectively shortening the growing season of the primary crop. Moisture content has a profound effect on soil response to machine traffic (Vomocil et al., 1958). The presence of dormant and dead crop residues can reduce evaporative losses of water from the soil surface. Crop residues can also help more moisture to infiltrate into the soil, thereby reducing surface runoff. High soil moisture conditions encountered during spring seedbed operations contribute to machine-induced compaction.

Surface residues, which complicate interactions between the soil and ground-engaging tools, affect the traction, mobility and steering of tractors and other field machinery (SRDC, 1993). The extent of such effects, and the means of minimizing them, are subjects of ongoing research. Maintaining cover crop root-shoot attachment is an approach to reducing management problems associated with planting into fragmented, desiccated residues (Vaughan et al., 1992). However, the effects of surface cover condition - succulent versus desiccated, attached versus fragmented - on tractive efficiency and machine mobility are as yet unknown.

Conservation tillage cropping systems have been developed to take advantage of the beneficial aspects of cover crops (NRC, 1989; Sullivan, 1990; Vaughan et al., 1992). Benefits of cover cropping versus fall-tilled fallow include: reduced soil erosion, enhanced nutrient retention, weed suppression, reduced tillage requirements, and the potential for

double cropping. Systems that utilize cover crops instead of, or in addition to, residues from a previous crop, provide above-ground biomass that is anchored to a root-enmeshed soil layer. Cover crop biomass that exists at the time primary crops such as corn and soybean are planted in the spring may cushion the soil from the damaging effects of machine traffic. Plant roots play a complex role in the alteration of soil mechanical properties. As a physical network within the soil, roots stabilize embankments by increasing soil shear strength (Abe and Ziemer, 1991; Terwilliger and Waldron, 1991). They are also active sources of organic exudates, which are likely to be effective agents in cementing and stabilizing aggregates (Soane, 1990).

The degree of compaction of a soil, characterized by its dry density, is dependent upon moisture content, the amount of compactive effort applied, and the nature of the soil (Jumikis, 1962). Compaction alters soil physical properties including hydraulic conductivity and macro- and micropore distribution. It has been argued that properties such as porosity and permeability characteristics are more meaningful indicators of soil response to compactive loads than the bulk density because these properties have a more pronounced influence on plant growth, drainage, and other factors of practical interest (Soane, 1990).

If surface residue and/or root fabric can be shown to attenuate the negative effects of machine traffic on soil properties, a forceful case can be made for maintaining an intact

cover crop presence. If cover cropping offers a passive, preventive alternative to tillage treatment of compaction, the traffic-tillage cycle can be broken and true conservation cropping systems developed. The farmer can be afforded protection from one of the unintended consequences of agricultural mechanization.

The work reported herein is an attempt to establish a foundation for the study of machine-soil interaction as affected by crop residues. I seek to answer the following question from a **soil compaction** perspective: *Is there a compelling reason for maintaining intact residue on and about the soil surface?* If the answer is, *Yes*, the next question becomes: *Does crop condition - succulent versus desiccated - cause a significant difference in soil response to machine traffic?* The final question is then: *Does the root reinforcement offered by an annual cover crop contribute significantly to any measured alteration in soil response to machine traffic?*

Objectives

My thesis is that cover-crop components, roots and above-ground biomass, alter soil response to machine traffic. The field research component of my doctoral program, supported by laboratory studies, provided data for the quantification of intact crop residue effects on machine-induced soil compaction. Characterization of machine-induced effects on the following soil parameters was the focus of the research:

- dry bulk density
- capillary porosity
- noncapillary porosity
- saturated hydraulic conductivity

Objectives of the research were to:

1. Evaluate the effects of above-ground rye (*Secale cereale*) residue condition - live versus desiccated - on machine-induced soil compaction;
2. Evaluate the separate contributions of root reinforcement and surface cushioning to the modification of soil response to machine traffic;
3. Evaluate soil response to single and multiple machine passes;
4. Investigate cover-soil type interaction effects on soil response to machine traffic; and
5. Investigate the effect of cover-crop biomass yield on soil response to machine traffic.

The following steps were taken to satisfy the aforementioned objectives:

1. Established a field experiment on two soils to compare four cover-crop residue treatments:
 - Live rye crop, intact
 - Desiccated rye crop, intact
 - Above-ground rye biomass removed
 - Fallow
2. Characterized the following physical properties for each soil type:
 - Atterberg limits
 - Standard Proctor moisture-density relationship
 - Particle-size distribution
3. Constructed laboratory apparatus to perform hydraulic conductivity and pore size distribution analysis;
4. Collected soil core samples from surface and subsurface zones in untracked areas and in machine traffic lanes;
5. Measured soil moisture content at the time of machine tracking; and
6. Measured cover crop biomass yields in each traffic zone.

Literature Review

Soil Compaction

In agriculture, machine traffic is the major cause of soil compaction (Håkansson et al., 1988). The term *compaction* generally refers to increases in packing state and destruction of structure in soils (Stafford and de Carvalho Mattos, 1981). Machine-induced increases in packing state and associated soil matrix volume changes are produced by momentary loading and can be measured by sampling soil bulk density. Destruction of soil structure modifies the pore volume and pore geometry of the soil. Measurements of soil pore size distribution and hydraulic conductivity provide evidence of compaction effects on soil structure.

Changes in bulk volumetric properties may not be as important to plant growth as the associated increases in soil strength and reduction of conductivity, permeability, and diffusivity of water and air through the soil pore system (Soane et al., 1981a). Plant roots must overcome the strength of the soil to penetrate pores of smaller diameters than themselves (Greacen and Sands, 1980). Reduced levels of root exploration caused by mechanical impedance may limit plant uptake of water and nutrients, particularly immobile phosphorous (Håkansson et al., 1988).

Aeration is one of the most important determinants of soil productivity. Adequate root growth requires that gaseous exchange take place between soil air and the atmosphere at a rate that prevents a deficiency of oxygen and an excess of carbon dioxide from developing in the root zone of a respiring plant (Hillel, 1971). Poor soil aeration can result in nitrogen losses from the soil via denitrification (Keeney, 1982). Macropores, critical to soil aeration and drainage, are lost first in the compaction process.

Micropores provide water holding capacity in a soil. Soils in which low bulk densities have been established through tillage tend to lack adequate water holding capacity and can actually benefit from recompaction. Stout et al. (1961) demonstrated that the benefits of firming the seedbed below sugar beets, corn, and beans were significant in soil with a low moisture content. The researchers concluded that seedbed and planting practices should promote maximum capillary flow of water to the seedbed. In addition, moderate soil compaction has been shown to increase root branching (Voorhees, 1977).

Although some degree of soil packing is necessary for plant growth in cropping systems that include pre-plant tillage, excessive soil compaction can produce marked, negative growth responses in field crops. An Indiana study showed that moderate subsoil compaction (zone depth = 20-23 cm; bulk density = 1.76 g/cm^3) reduced corn yields by 25 percent. Severe compaction (bulk density = 1.82 g/cm^3) reduced corn yields by over 50 percent (Gaultney et al., 1982). Canarache et al. (1984) reported a 13 kg/ha decrease

in corn grain yield for each 1 kg/m^3 (0.001 g/cm^3) increase in soil bulk density based on results from a four-year field study conducted in Romania. Corn, cereal grains, and cotton have shown significant yield responses (generally negative) to compaction under field conditions on a global scale (Voorhees, 1991).

The degree of compaction that occurs due to machine traffic is related to the types of loading imposed on the soil surface (Soane et al., 1981b). Three primary types of forces are exerted on the soil during the passage of a driven wheel: the downward force resulting primarily from the weight of the vehicle, the shear stress resulting from axle torque exerted on the wheel, and vibration transmitted from the engine to the soil surface via the tire body. The difficulty associated with reproducing the three types of forces, accurately and simultaneously, in the laboratory is a compelling reason to undertake field testing of machine-induced soil compaction.

Factors That Affect Soil Compaction: Soil pressures caused by agricultural equipment are determined almost exclusively by characteristics of the equipment and its operation (Chancellor, 1977). However, the degree of compaction resulting from machine traffic is related to soil properties such as moisture content, particle size distribution, plasticity index, initial compactness, and organic matter content (Soane et al., 1981a; Stafford and de Carvalho Mattos, 1981).

Compaction of soil that is not fully saturated involves an expulsion of air without significant change in the amount of water in the soil mass (Bradford and Gupta, 1986). The effect of soil moisture content on soil compactibility can be measured by a procedure called the Proctor test (Liu and Evett, 1990). The maximum density to which a soil can be compacted normally results from a moisture content near field capacity (Jumikis, 1962). When used as a construction material, soil is often manipulated to achieve a high degree of compaction. The moisture content at which a soil can be compacted to the maximum dry density for a given level of compactive effort is called the *optimum moisture content*. This "optimum-water-content" effect is related to a loss of the lubricating action of water films at water contents below the optimum and the limited air voids available for displacement above the optimum (Soane et al., 1981a). The pattern of real compaction under tire loads has been found to compare well with the standard Proctor compaction test (Raghavan et al., 1976).

The state of consistency of a soil between the solid and liquid ranges has been defined in terms of Atterberg limits (Ghildyal and Tripathi, 1987). The liquid limit for a soil is the moisture content at which the soil is practically liquid but possesses some limited shearing strength. At, or above, the liquid limit, the soil mass flows under an applied load. The plastic limit for a soil is the moisture content threshold at which there is sufficient water to provide a film around each particle. When the moisture content falls between the liquid and plastic limits, a soil exists in a plastic state, capable of being deformed without volume

change. The numerical difference between moisture contents at the liquid and plastic limits, the *plasticity index*, increases with increasing clay content (Mitchell, 1976). The greater the plasticity index, the more slowly soil strength changes with water content (Dexter, 1988).

In very wet to saturated soils, wheel traffic can produce sinkage and general shear failure without compaction due to poor drainage in the soil under the load. Soil flows from beneath the wheel and is displaced from its original position. In such cases, soil structure is destroyed with accompanying detrimental effects on infiltration and increased runoff (Greacen and Sands, 1980; Tippett, 1992). Also, the resultant soil surface depression has the potential to interfere with subsequent field operations (Blackwell et al., 1986).

Akram and Kemper (1979) tested soils ranging in texture from loamy sand to silty clay to determine infiltration rates, volume reduction, and bulk densities as a function of compacting pressure and moisture content at the time of compaction. Maximum compaction generally occurred when the soils were compacted at moisture contents near field capacity. When compacting loads were less than 1 kg/cm^2 , the resultant bulk densities were minimum when the soil samples had moisture contents of about one-half field capacity. The results indicate the major role of water-film surface tension in promoting cohesiveness and stability against compaction under such loading and moisture conditions.

Compacting loads of 3.46 kg/cm^2 on sandy loams and finer-textured soils at field capacity reduced infiltration rates to less than 0.1% of air-dry compaction values (Akram and Kemper, 1979). Infiltration reduction in a loamy sand soil was to about 1% of air-dry values. Relatively low air-water interface and capillary pressures at field capacity apparently reduced cohesive forces to such a degree that soils could no longer withstand compaction loads. Such significant compaction produced by rather ordinary loads indicates the potential for deleterious soil physical effects resulting from routine machine traffic.

Loading of soil will cause compaction only if a certain level of stress, called the *pre-compaction stress*, is exceeded (Dexter, 1988). For a given moisture content, pre-compaction stress is equal to the maximum compaction stress previously applied to a soil. Soils that exist in a loose state of packing are more vulnerable to particle rearrangement and further packing than are soils in a denser state (Davies et al., 1973). Furthermore, Dexter and Tanner (1974) observed that a soil in an undisturbed condition was less susceptible to compression than the same soil after remolding. They related the higher strength of the undisturbed state to the effect of interparticulate bonds that form over time within a soil. The researchers contended that soils that have been tilled are more susceptible to compression than soils devoted to zero tillage cropping practices.

Soane et al. (1981a) reported that for 58 Scottish soils, there was a close negative correlation between organic matter content and maximum bulk density obtained with the Proctor test. They speculated that increased organic matter levels resulting from long-term no-tillage may lead to a considerable additional reduction in soil compactibility.

Organic matter can promote soil aggregate formation by supplying cementing agents such as polysaccharides (Miller and Donahue, 1990). Soil voids develop as cycles of wetting and drying form cracks in the soil mass, which are preserved by cemented soil particle structures. Soane (1990) contended that maintenance of aggregate stability through appropriate crop management practices would enhance soil resistance to compactive loads. Not all strength indices of soil are improved by the addition of organic matter, however.

The effect of water conditions (wetting and drying cycles) and organic matter on paddy soil strength was examined by Yuan and Zhao (1981). Their research revealed that the modulus of rupture of three paddy soils actually decreased with an increase in organic matter content. The modulus of rupture of the soils was measured by applying pressure to dried soil cores. Each cylindrical sample was compressed laterally until tensile failure resulted. The authors hypothesized that since organic matter promotes aggregation, the number of surface contacts among soil particles was reduced, thereby reducing soil strength as measured by the modulus of rupture. Reduced soil tensile strength might

enhance the abilities of roots to crack soil by means of the tensile stresses they exert (Dexter, 1988).

The potential for altering soil behavior by adding organic matter to mineral constituents must be assessed realistically. To raise the organic matter content of a 30-cm thick layer of soil by one percentage unit would require about 45 t/ha of material (Unger et al., 1981). The average rye silage yield in the state of Virginia ranges from 2.4 to 3.9 t/ha dry matter; the corn silage yield ranges from 11.0 to 19.6 t/ha dry matter (VCES, 1987). At a typical grain-to-straw ratio of 1:1 (Gupta et al., 1987), a continuous grain cropping system could generate crop residues equal to one half of the aforementioned yields. The magnitude of potential residue contributions, combined with the fact that not all crop material additions become stable organic residues in the soil, clearly illustrates the long-term nature of crop-based organic-matter building measures. Dexter (1988) estimated that it would take 20-40 years for low organic matter contents to be increased toward a new, higher equilibrium content by the growth of continuous pasture on a Red-brown earth.

Soil Properties Affected By Compaction: When soil is compacted, soil strength is increased and total porosity is reduced at the expense of the large pores. Volumetric water content and field capacity are increased, while air content, water infiltration rate, and saturated hydraulic conductivity are decreased. Consequently, surface runoff of water

may increase and crop growth may be reduced because of a reduced water supply, restricted root space, and poor aeration (Greacen and Sands, 1980).

Although the effects of soil compaction on plant growth represent a complex interaction among many soil and plant properties, researchers have identified threshold values for certain soil properties that indicate the potential for severely restricted plant growth. Excessive soil strength can materially inhibit or divert root growth from normal patterns. Gaultney et al. (1982) found that corn root elongation ceased at penetration resistance levels above 1800 kPa. Cotton roots could not penetrate soil layers that offered 3000 kPa resistance regardless of whether the high resistance was caused by increased soil bulk density or by reduced soil water content (Taylor et al., 1966).

Greacen and Sands (1980) related the stress applied by a compacting load to the resultant penetration resistance of a soil. They determined that for a remolded surface soil in equilibrium with a compacting load σ_1 , the point resistance measured by a penetrometer was approximately $10\sigma_1$. The researchers concluded that soil being compacted by a vehicle tire that exerted a pressure of 250 kPa would eventually reach an equilibrium state of compaction that would produce a penetration resistance of 2500 kPa, a critical value for root growth in many species of plants.

The strength of a soil, as measured by penetration resistance, is a function of soil bulk density and moisture content (Ayers and Perumpral, 1982; Ohu et al., 1985). Compacted soils provide the lowest mechanical impedance at field capacity (Bowen, 1981). At such high water contents, mechanical impedance can be estimated from soil bulk density.

Soil texture has a major effect on the average pore size and mechanical resistance of a compacted soil. A soil with a high proportion of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a high proportion of coarse particles (Daddow and Warrington, 1983). Taylor et al. (1966) determined growth-limiting bulk densities for cotton grown on a range of soil types. There was no cotton root penetration into a Miles loamy fine sand (83% sand, 8% silt, 9% clay) at a bulk density of 1.82 g/cm³. Root penetration was arrested at the much lower bulk density of 1.55 g/cm³ on a Columbia loam (44% sand, 37% silt, 19% clay). Dannowski (1992) reported essentially unrestricted rye root growth in a faint loamy sand (80.8% sand, 13.8% silt, 5.4% clay) at a bulk density of 1.65 g/cm³. However, the root growth performance of triticale, a hybrid produced by crossing durum wheat (*Triticum durum*) and rye, suffered versus its level at a 1.50 g/cm³ bulk density. Crop growth response to soil strength varied not only by species, but by variety within species.

In spite of the understood variability among crops, Bowen (1981) summarized the relationships between soil texture and bulk density that will produce severe impedance of

root growth: clay loams - 1.55 g/cm^3 , silt loams - 1.65 g/cm^3 , fine sandy loams - 1.80 g/cm^3 , and loamy fine sands - 1.85 g/cm^3 . Daddow and Warrington (1983) modified the soil textural triangle to illustrate the relationships between bulk density and soil texture that result in crop growth limitation (Figure 1). The growth-limiting bulk density (GLBD) for a given soil can be estimated by locating its percent sand, silt, and clay on the textural triangle, then determining the appropriate GLBD value (in g/cm^3) associated with that point. Linear interpolation can be used to determine the GLBD for a soil with a textural value that falls between a pair of isodensity lines.

Daddow and Warrington (1983) sought to provide soil scientists with a tool for estimating the threshold at which restricted root penetration and elongation could cause a reduction in total plant growth on many different kinds of soils. Soil bulk density was chosen as the appropriate parameter for evaluating the relationship of soil texture to compaction and plant root growth because bulk density values appeared to be less dependent on soil moisture and measuring techniques than soil strength values.

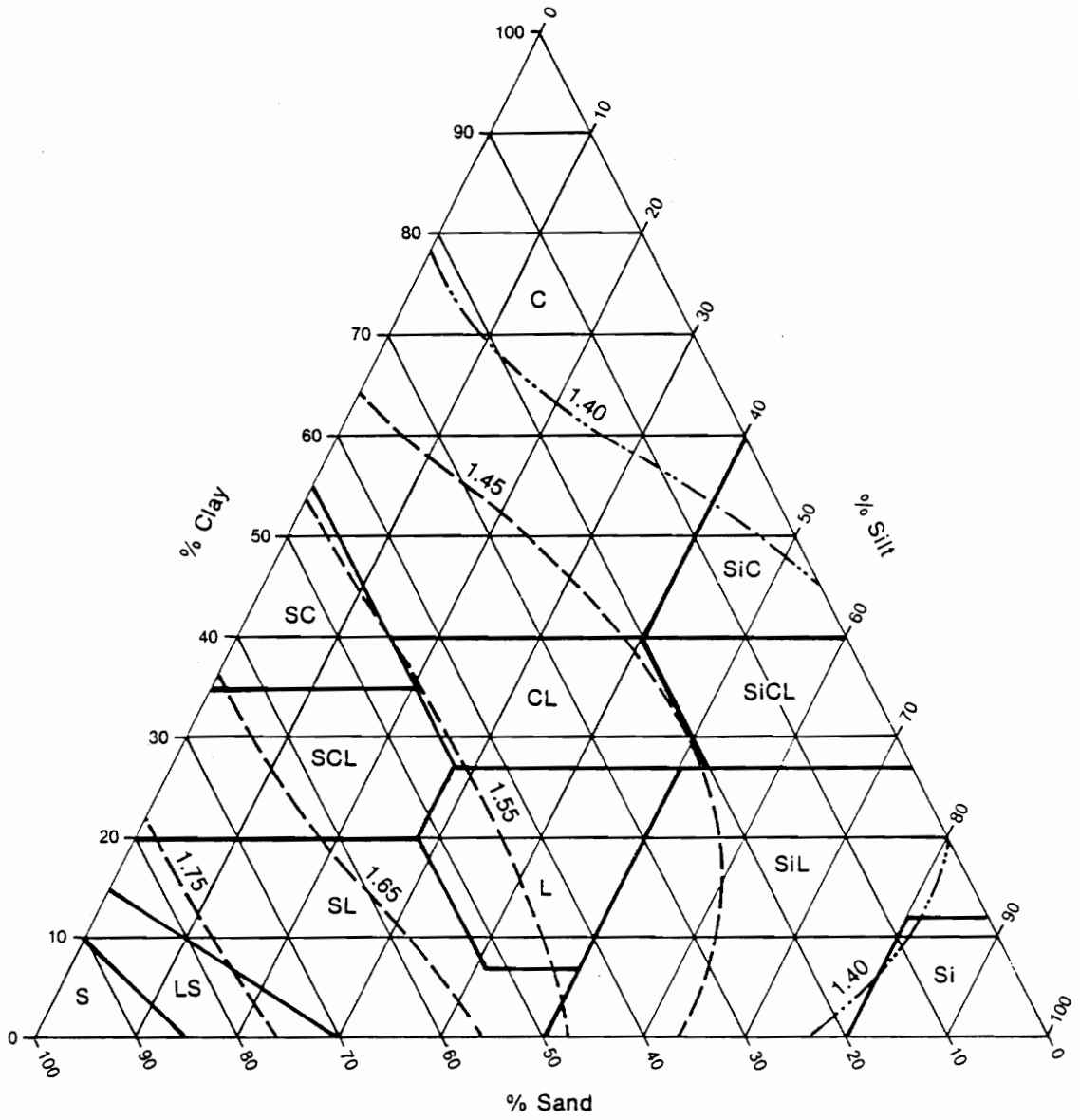


Figure 1. Growth-limiting bulk density textural triangle.

Soil porosity and bulk density are inseparably linked. While bulk density characterizes the proportion of soil volume occupied by solids, total porosity characterizes the proportion of voids occupied by water and air. Treatments that increase bulk density decrease total soil porosity; however, total porosity measurement is of limited value (Dexter, 1988). Pore size distribution, the measure of capillary and noncapillary pore volumes (Vomocil and Flocker, 1961), provides much more insight into the air and water holding and transmission characteristics of a soil. Large pores and cracks are important for soil drainage, aeration, and root access; smaller pores store soil water and are the sites of nutrient retention and microbial activity (Childs et al., 1989). The need for a mixture of capillary and noncapillary pores in agricultural soils is clear.

Pore size distribution of soils is described on the basis of a capillary model (Vomocil and Flocker, 1961). In the capillary model, a soil is idealized as a bundle of short capillary tubes of various sizes. Based on the concept of continuous cylindrical pores, water matric potential has been related to pore radius by the following expression (Gupta et al., 1989):

$$\text{Pore size } (\mu\text{m}) = \frac{150}{\text{Matric Suction (kPa)}}$$

Field capacity, for many practical purposes, corresponds to a matric suction of 10 kPa, or an equivalent pore diameter of 30 μm (Dexter, 1988). Air-filled porosity at a matric suction of 5 kPa (60 μm equivalent pore diameter) has been used as an index of *aeration porosity* (Heard et al., 1988). Noncapillary porosity is also referred to as aeration porosity.

Reduced soil aeration is likely to become limiting to plant growth when the air-filled porosity falls below about ten percent at field capacity (Hillel, 1971). When there is more than about ten percent air-filled pore space, and continuity among the pores, the oxygen concentration in the bulk soil can be maintained at atmospheric levels by gas diffusion.

Childs et al. (1989) presented a generalized model relating root growth conditions to soil strength, moisture, bulk density, and aeration. Model output, illustrated in Figure 2, shows root growth "windows" for a loam soil at various levels of bulk density bounded by soil conditions of excessive strength and inadequate aeration. It should be noted that as bulk density increases, the root growth windows become more narrow.

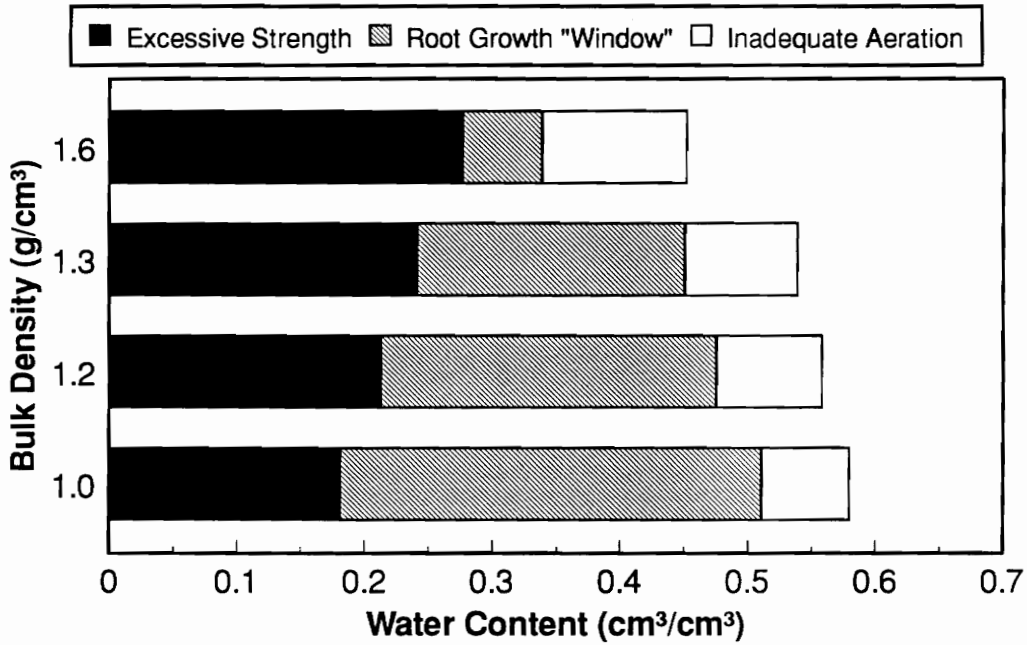


Figure 2. Soil strength and aeration limits for optimizing root growth (Reicosky et al., 1981; Childs et al., 1989).

The saturated hydraulic conductivity (K_{sat}) of a soil is crucial to adequate infiltration and drainage. Soil characteristics that affect hydraulic conductivity are total porosity, the distribution of pore sizes, and pore tortuosity - in short, the pore geometry of the soil (Hillel, 1971). Large pores, cracks, worm holes, and decayed root channels can contribute greatly to measured conductivity under saturated conditions. Zobeck et al. (1985) reported that for two clay-rich Ohio soils, the mean vertical K_{sat} of the soil with macropores varied from 20 to over 100 times that of the soil without macropores.

Since laminar flow within capillary tubes varies with the fourth power of the tube radius (Vomocil and Flocker, 1961), and since it is the large interaggregate pores that are lost first during compaction (Cruse and Gupta, 1991), the effects of soil compaction on saturated hydraulic conductivity can be striking. Davies et al. (1973) reported that the mean water penetration rate into a Terrington silt loam soil dropped from 82 cm/h in untreated zones to 1.9 cm/h in wheel tracks made by a single pass of a small tractor (rear axle load = 2 Mg). Heard et al. (1988) identified a critical bulk density of 1.50 g/cm³ for low saturated hydraulic conductivity on a Clermont silt loam soil in Indiana. As the maximum bulk density within the top 40-cm layer of sampled soil columns increased from 1.49 to 1.55 g/cm³, measured K_{sat} means were reduced from 11.6 to 2.2 cm/h. Vomocil et al. (1958) observed that a machine-induced increase in soil bulk density of less than 10 percent (1.40 to 1.50 g/cm³) was accompanied by a more than tenfold reduction in infiltration rate (2.08 to 0.13 cm/h) on a loam soil.

Micropores are less affected by compaction than are macropores. Soil pore size distribution changes as the proportion of micropores increases (Davies et al., 1973). Cruse and Gupta (1991) noted an increase in water retention at matric suction levels greater than 1.0 kPa as a Nicollet clay loam soil was compacted through a range of bulk densities from 1.09 to 1.66 g/cm³. Since most agricultural crops can extract water from the soil until water suction is around 1500 kPa (0.2 μ m equivalent pore diameter), soil

storage of plant-available water is maximized when the volume of pores between 30 μm (field capacity) and 0.2 μm is maximized.

Figure 3 illustrates the relationship between pore size distribution and water availability for a loam soil. The chart shows that plant-available water is $0.17 \text{ cm}^3/\text{cm}^3$ for the soil at a bulk density of $1.0 \text{ g}/\text{cm}^3$ (Childs et al., 1989). Compaction to bulk densities of 1.2 and $1.3 \text{ g}/\text{cm}^3$ increases the amount of plant-available water to 0.21 and $0.20 \text{ cm}^3/\text{cm}^3$, respectively. At a bulk density of $1.6 \text{ g}/\text{cm}^3$, the level of plant-available water decreases to $0.13 \text{ cm}^3/\text{cm}^3$. Compaction initially shifts the pore-size distribution away from pores that are drained by gravity, thereby increasing water storage. Excessive compaction decreases total porosity while significantly increasing the proportion of pores that will not release water for uptake by plant roots.

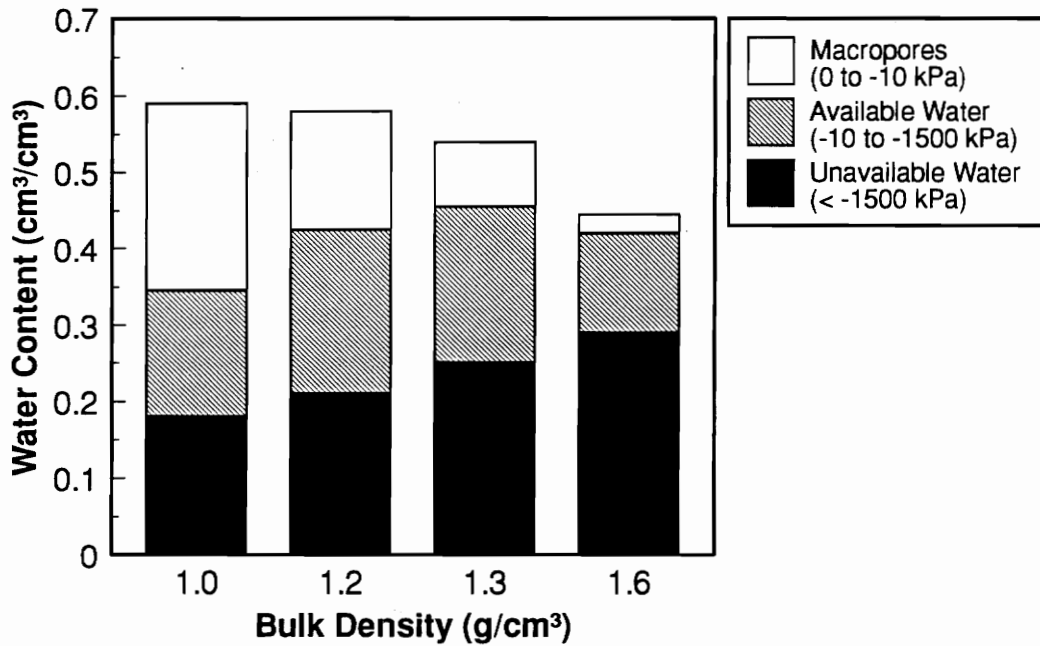


Figure 3. Change in pore size distribution and water availability with compaction for a Barnes loam at four bulk density levels (Reicosky et al., 1981).

The compression of a soil is accomplished by means of a reduction in effective mean pore diameter (Dexter and Tanner, 1974). An increase in the proportion of smaller pores changes not only water retention characteristics, but water transmission characteristics as well. Unsaturated hydraulic conductivity suffers less reduction due to compaction than does K_{sat} . In fact, compaction can increase the unsaturated hydraulic conductivity of a soil (Greacen and Sands, 1980). As with all other aspects of soil response to machine traffic, a number of soil and machine variables interact to produce an effect, positive or negative, on agricultural crop production.

Machine-Soil Interaction

The extent of machine-induced soil compaction depends on factors such as axle load, tire inflation pressure, the number of vehicle passes, wheel slip, and vehicle travel speed. A compaction study conducted on fall-plowed fields in Sweden related the degree of soil compaction resulting from tractor traffic the following spring to a range of soil and machine variables (Håkansson et al., 1988). The variables could be sorted in the following order, according to their influence on compaction in the tilled layer (0 - 25 cm): soil moisture (most important), number of passes by the wheels, tractor weight, wheel equipment (singles or duals), tire inflation pressure, speed and draft (virtually unimportant). Wheel load, soil moisture content, and the number of vehicle passes were identified as the factors most decisive for subsoil compaction.

Initial soil strength largely determines the manner in which soil compaction changes following the first and subsequent machine passes. Soils which are initially loose will show much larger increases in compaction during the first pass than in subsequent passes. On soils with appreciable initial strength, the compaction resulting from the first pass will differ little from that of subsequent passes (Soane et al., 1981a). The initial pass over a freshly-tilled soil by a powered wheel has been shown to account for 75 percent of the total change in soil bulk density resulting from four passes in the same track (Taylor et al., 1982). Davies et al. (1973) found that 80 percent of the sinkage, 84 percent of the

increase in density, and 75 percent of the increase in shear strength resulting from three machine passes took place in the first pass over a tilled silt loam soil.

Lenhard (1986) examined bulk density and moisture retention effects on a forest soil after 0, 1, 2, 4, 8, 16, and 32 trips with a rubber-tired skidder. Bulk density reached a maximum after four trips and remained statistically constant with additional trips. Greene (1983) investigated the effects of log-skidding machine and tire size on the compaction of two silt loam forest soils in Georgia. He reported that surface-layer soil bulk density increased significantly following one and three machine passes, but that compaction measured after ten passes had not changed statistically from three-pass levels.

Burger et al. (1985) found that soil density and porosity changed proportionally with the square root of the number of passes of log-skidding equipment on a forest soil. Canarache et al. (1984) related effects of wheel traffic on soil physical properties to the number of tractor passes according to regressions of the type $Y = a X^b$ (where Y = soil property and X = number of passes). The Romanian field study was conducted over a four-year period in four locations with different soil types and climatic conditions. Most of the machine-induced soil property changes were recorded between 0 and 8-10 passes, with negligible changes following 15-20 passes.

The general principle that applies to pneumatic tires is that the average pressure exerted by the tire on the tire-soil interface is approximately equal to the inflation pressure (Chancellor, 1977; Håkansson et al., 1988; Erbach and Knoll, 1992). A pneumatic tire flattens to increase contact area in response to increasing vertical load, thereby maintaining mean contact pressure.

Although mean soil-tire contact pressure relates closely to tire inflation pressure, the pressure distribution can be highly non-uniform over the contact area due to lug (ASAE, 1993b) and sidewall effects. Under smooth tires, sidewall stiffness can produce peak contact pressures that are two to five times inflation pressure (VandenBerg and Gill, 1962). Burt et al. (1989) noted pressure concentration effects due to sidewall stiffness under lugged, radial-ply tractor tires. The carcass stiffness effect becomes more pronounced at low inflation pressures, thereby undermining attempts to benefit from reduced mean ground pressure. Horn and associates (1989) measured vertical stress values of up to 300% more than average tire contact pressure at a soil depth of 20 cm. They attributed the high stress levels to load transmission by lugs and noted similar effects associated with sidewall stiffness.

Soil and tire characteristics interact to affect contact pressures. On compacted soils, a tire tends to assume the shape of the soil surface whereas the soil tends to conform to tire shape in low density conditions. A combination of high inflation pressure and soft soil can

produce rigid wheel behavior (Håkansson et al., 1988) and contact pressure peaks that are lower than inflation pressures. Under dynamic loading conditions, the normal stress at the interface between the edge of a radial-ply tractor tire and uncompacted soil approached tire inflation pressure as dynamic loading increased from 5.9 kN to 23.4 kN; on firm soil, normal stress peaked at about two times inflation pressure (Burt et al., 1989).

The distribution of stress over the contact area between a tire and the soil surface and the contact area itself are very difficult to measure, especially for lugged tires (Soane et al., 1981b). Measurement of pressure distributions at the tire-soil interface is hindered by instrumentation requirements and the in-field variability of soil and tractive conditions. As a result, mean contact pressure (wheel load divided by estimated contact area) is typically reported for field studies (Greene, 1983; Minaei, 1984; Burger et al., 1985; Lenhard, 1986; Gupta et al., 1987; Horn et al., 1989).

Depth of compaction is of interest inasmuch as it indicates whether remedial efforts can be successful and how much energy must be spent to effect a remedy. Authors speak of the tilled layer, or the *tillage zone*, in relation to the severity of machine-induced compaction (Bashford et al., 1988). Gupta and Allmaras (1987) expressed concern for compaction at depths of 20 cm and more because the effects occurred below the usual tilled zone. Subsoiling can reduce compaction at depths greater than the working range of primary

tillage tools; however, slow working speeds, high horsepower and energy requirements, and high initial investments are added costs (Sharpe et al., 1988; Vaughan et al., 1978).

Chancellor (1977), in describing the vertical pressure distribution under a concentrated surface load, stated that pressures generated near the soil surface are mainly a function of pressures applied by the equipment, whereas pressures generated at some depth within the soil are mainly a function of wheel load. Greacen and Sands (1980) reported that for heavy loads (on the order of 16 Mg), it is largely the load and not the contact pressure that determines the magnitude of the stress at depths of 40 cm or more. Håkansson et al. (1988) asserted that compaction to a depth of 40 cm or more is frequently observed when axle load exceeds 6 Mg.

Jakobsen and Moore (1981) were able to detect compaction effects on soil penetration resistance at a depth of 25-30 cm on logging trails after 15 traffic cycles by tracked vehicles. The experiment was conducted in a mountain ash forest on a well-graded soil (45% sand, 22% silt, 33% clay) with vehicles weighing as much as 21,000 kg. Logging with large track-type tractors compacted major skid trails on a sandy clay loam forest soil to a depth of 30 cm with effects evident 16 years after traffic ceased (Froehlich, 1979).

In a study comparing the impact of a 14,900-kg tracked tractor and a 7,600-kg rubber-tired tractor on a clayey forest soil, Burger et al. (1985) found that neither soil

density nor porosity was affected at or below a depth of 15 cm, however. Each vehicle was driven over the same path as many as nine times. The authors contended that although compaction to 30 cm had been reported for heavily-used skid trails, typical forest harvesting operations did not result in compaction to depths greater than 15 cm.

Voorhees et al. (1978) showed that repeated wheel traffic (five to six tractor passes per season) by agricultural vehicles weighing from 3,700 to 7,300 kg caused significant increases in bulk density at a 15- to 30-cm depth in four years of a five-year compaction study. The study was conducted on a silty clay loam soil in Minnesota. Field procedures were typical of a conventional-tillage row crop farming enterprise in the northern Corn Belt, but traffic was restricted to the same lanes for every operation. Concentrating traffic in selected zones reduces the overall compacted area in a field, but repeated loading results in an increased depth of compaction (Kayombo and Lal, 1986).

In general, the degree of compaction under tractor wheels can be assumed to decrease with an increase in ground speed. Dexter and Tanner (1974) observed that various time- and rate-dependent effects operate when soils are deformed, producing apparently greater soil rigidity as deformation becomes more rapid. They also found that soils composed of small particles take longer to compress than those composed of large particles. Soils with smaller particles also have pore spaces of smaller mean diameter. The relationship

between particle/pore size and compression time was attributed to the viscosity of pore fluid.

Stafford and de Carvalho Mattos (1981) studied the effect of vehicle speed on soil compaction in the laboratory and in the field. In the laboratory, compaction of soils increased with load pulse duration for soils drier than the plastic limit, but not for those that were wetter. Field experimentation showed an increase in compaction of soil by wheels over a wide range of moisture contents as speed decreased. The widening of the moisture content range in the field was attributed to the addition of shear strain-induced compaction due to wheel slip, the effect of which was less at higher speeds. It was also noted that the speed effect was larger at lower soil bulk densities.

Horn et al. (1989) measured stress and soil physical property changes resulting from the passage of a heavily loaded (4 Mg) wheel operated at different speeds up to 8 km/h. The experiment was conducted on a Red-brown earth (40% sand, 16% silt, 44% clay) at different water contents, all near the soil's plastic limit. Effective stress measured at a depth of 35 cm declined in magnitude and duration as wheel speed increased. Total stress measured at a depth of 20 cm increased with wheel travel speed, apparently due to large pore water pressures, but shear stresses changed little. Based on trends in the data, the researchers predicted a ten percent decrease in final bulk density at a depth of 20 cm due to a travel speed increase from 0.5 to 10 km/h.

Research into the effect of travel speed on soil compaction has produced varying, sometimes contradictory quantitative results (Soane et al., 1981b). Håkansson et al. (1988), addressing conflicts in the literature, pointed to a condition that arises when traffic is carried out on normal, rough field surfaces rather than artificially smooth soil bin surfaces. The bouncing motion of tractors, when driven at speeds above 7 km/h on fields with rough surfaces, tends to counteract the potential of higher speed to reduce compaction. Vomocil et al. (1958), in an early, and often-referenced study of vehicle speed and drawbar load on compaction, provided another instructive addition to machine-soil interaction discourse. The researchers stated that, "...soil moisture content, a factor which the tractor designer cannot control, seems of overwhelming importance in determining the degree of structural damage caused by traffic. In comparison with moisture content changes, the effect of speed was quite unimportant."

Plant Material Effects on Machine-Soil Interaction

The effects of surface residues on machine-soil interaction have been the subject of a limited number of field studies involving forestry operations. Miles (1978) compared soil bulk density changes produced by logging on major and minor skid trails. Major skid trails had been stripped of organic cover. Minor skid trails were those covered to some

degree by duff (e.g., fallen leaves), which had been 6 to 8 cm deep on the undisturbed surface. Although the scouring action of logs produced highly variable levels of compaction within skid trail profiles, bulk density differences caused by logging traffic on trails protected by organic matter were less than half those observed on major trails. Differences were more pronounced at high soil moisture levels.

Jakobsen and Moore (1981) examined the possible protective effect of a slash cover on skid trails traveled by tracked vehicles weighing in excess of 12.5 Mg. The slash, cut from the ash forest understory into 1- to 2-m lengths, was spread evenly over the traffic zone at a rate of **180 Mg/ha**. The researchers measured traffic effects on the bulk density, pore size distribution, hydraulic conductivity, and penetration resistance of the Kraznozem soil (45% sand, 22% silt, 33% clay) following one, three, seven, and fifteen traffic cycles. Some soil property differences were recognized after one cycle, but a marked difference between the bare soil and the slash-covered areas was apparent after three cycles; air-filled porosity was 79 percent greater and penetration resistance was 89 percent less for the slash-covered treatment versus bare soil. After seven cycles, differences between the treatments were negligible. It was concluded that a slash cover offered some soil protection, but only for a few cycles.

Johnson et al. (1979) measured the effect of leaf litter on soil compaction resulting from log skidder traffic. Penetration resistance resulting from one machine pass was lower for

litter-covered soil than for bare soil (0.81 versus 1.06 kg/cm²). The litter-covered treatment remained less compacted after multiple passes, as well (1.15 versus 1.31 kg/cm²). The penetration resistance results led the authors to conclude that, "Leaf litter is essential in reducing apparent compaction, since it acts as a blanket to distribute the forces of compaction over a larger area than where the force is applied." It must be noted, however, that the absence of moisture content data and analysis of variance results from the research report calls the sweeping conclusion into question.

In a study pertaining to agricultural crop production, Gupta and associates (1987) investigated the effectiveness of surface-applied crop residues in reducing compaction effects resulting from wheel traffic. Chopped corn residues acted as a cushion, reducing the level of stress measured 20 cm below the center of a tractor wheel track in a soil bin experiment conducted on a Waukegan silt loam. However, the reduction in measured stress was not large enough (< 80 kPa) to cause "any great change" in the soil matrix-water-air relationship due to a single tractor pass. The use of the unspecific phrasing, "any great change", probably stemmed from the fact that measured bulk densities were greater under residue treatments than under no cover in spite of the fact that measured stress values were lower. No explanation of the phenomenon was offered. At residue application rates of 10.1 t/ha or less, there was no statistically significant reduction in the bulk density of the silt loam soil at moisture contents ranging from 16 to 21 percent.

Gupta et al. (1987) hypothesized that surface residues may slightly reduce wheel sinkage and the propagation of stresses despite the lack of evidence that residues acted to distribute the forces of compaction over a larger area than where the force was applied. In fact, the 6.7 Mg/ha residue treatment produced bulk densities that were significantly ($p < 0.01$) different with distance away from the center of the wheel track, but numerically less than under the bare soil treatment at distances of 25 and 35 cm from the wheel-track center (wheel track half-width = 22.8 cm).

Hulugalle and Palada (1990) examined the effect of seedbed preparation method and mulch on soil physical properties in cowpea production on a loamy sand in Nigeria. At an application rate of 4 Mg/ha, rice straw mulch had no effect on compaction but decreased soil temperature and increased moisture content. NeSmith et al. (1987) reported that the water content in the upper 10 cm of a Greenville sandy clay loam in Georgia was 30 to 40 percent higher in no-tillage plots covered by wheat residue than in plots with no vegetative cover. Childs et al. (1989), in discussing surface organic layers, observed that deeper in the soil profile, where soil compaction and strength increases are affected by soil water content, any change in water status caused by organic matter indirectly affects soil strength.

Guérif (1979) compared results of Proctor tests performed on a mineral soil (85% sand, 15% clay) and on a mineral soil-wheat straw mixture (2% straw < 2 mm). The straw

addition was shown to decrease sample density at any given water content and increase the plasticity index of the soil. The results were explained by the sterical effect of straw, which would not allow a close packing of soil aggregates. Further experimentation revealed that the elasticity of straw decreased as it decayed, thereby reducing its effectiveness in improving the behavior of soil subjected to compressive loads.

Soil compressibility can be measured by uniaxial compression testing in which soil is compacted in a rigid cylinder by a downward-moving piston (Koolen and Kuipers, 1983). Gupta et al. (1987) investigated the influence of incorporated corn residue on the compression behavior of a clay loam, a silt loam, and a sandy soil as measured by uniaxial compression testing. Treatments included three size fractions (0.25-0.50, 1.00-2.00, and 3.36-5.66 mm), four amounts of residue addition (0.0, 0.5, 1.0, and 2.0 g of corn residue / 60 g wet soil), and three water contents for each soil. The compression characteristics of the clay loam and silt loam soil-residue mixtures were approximately the same for the various amounts and sizes of corn residues. Residue incorporation actually increased the compressibility of a Zimmerman sand. It was proposed that separation of the mineral fraction by residue reduced the friction forces resisting soil compression. The researchers concluded that corn residues available on the farm will have little value in reducing the susceptibility of soils to compaction if the residues are incorporated into the soil - even if the residues from a 6.7 t/ha (100-bushel) corn crop are concentrated in wheel traffic zones.

Living and, to a lesser extent, dead roots have a marked effect on the strength characteristics of soil (Soane, 1990). Apart from acting as a physical network, roots are an active source of organic exudates which are likely to be effective agents in stabilizing aggregates. The bearing capacity of soils containing root networks of spruce was shown to be up to 70 percent greater than in similar soils without roots (Greacen and Sands, 1980). Hassan (1978) reported that the presence of a root mat layer on a forest soil (a coarse sand overlain by a 30- to 45-cm thick organic layer) increased soil machine support (bearing capacity) by a factor of three versus bare soil. The claim was based on the measured difference in penetration resistance of the first 10-cm zone in the soil profile with the root mat undisturbed and with it removed. The author, however, did not provide moisture content data to support the extraordinary experimental result.

Waldron (1977) demonstrated the effectiveness of roots in increasing soil shear strength. To measure the mechanical reinforcement offered by roots of alfalfa, barley, and yellow pine, direct shear tests were conducted on 25-cm diameter root-permeated columns. Each plant species increased the shear resistance of homogeneous and compacted layers of silty clay loam at a depth of 30 cm. The roots of rice plants have also been shown to produce significant increases in soil shear strength (Hunter, 1991). Increased soil shear resistance due to root reinforcement results from the stretching, slipping, and breaking of roots of various sizes (Waldron and Dakessian, 1981).

The maximum total root length of cereal plants is attained at anthesis (flowering), when wheat plants may have 50-100 m of roots reaching to a depth of 2 m in well-structured soils (Goss, 1987). The strength of soil increases proportionally to the concentration, or cross-sectional area, of root fibers in the soil (Wästerlund, 1989). Cereal crop root densities in the topsoil can reach values of 10 cm/cm³, corresponding to a mean spacing between roots of only about 3 mm (Dexter, 1988).

Abe and Ziemer (1991) proposed a model that uses root strain to estimate the shear stress of soil reinforced by roots. The presence of roots in soil tested in a direct shear device was shown to cause a widening of the shear zone, requiring each soil particle to move less than when the shear zone was narrow. Although there is no accepted approach to relating soil shear strength to soil compaction (Soane et al., 1981a), the idea of force redistribution provides a sense of the mechanism by which roots could increase soil compaction resistance. Soane (1990) suggested plant roots provide a filamentous network that, like geotextiles (Ingold and Miller, 1988), can enhance the resistance of a soil to compactive loads.

The review of research into plant material effects on machine-soil interaction led to several general conclusions:

1. Surface residues can provide some protection against machine-induced compaction of forest soils,
2. Residues encountered in forestry operations can differ markedly from agricultural crop residues in regard to morphology and yield,
3. Surface residues in the forest and in the field can indirectly affect compaction by altering soil moisture content,
4. Incorporated plant residues afford insignificant protection against machine-induced compaction,
5. The degree of residue decomposition affects its contribution to the compressive strength of soil,
6. Plant roots can increase the shearing strength of soil, and
7. An undisturbed mat of tree roots can significantly increase the bearing capacity of a forest soil.

This work attempts to build upon conclusions reached in the laboratory and in the forest and assess the potential of a cover crop with an undisturbed root mass to alter soil response to machine traffic.

Description of Analytical Methods

Experimental Design

A block is a group of experimental units that provides homogeneous effects on a response variable. In the basic randomized complete block (RCB) design, all treatments appear once in each preselected, homogeneous block. Arrangement of experimental treatment units within each block is randomized. A *generalized*, randomized complete block design was used to investigate the effects of cover crop components on machine-induced soil compaction. The generalized RCB design is an extension of the basic RCB design in which each treatment appears multiple times within each block.

Blocking is a form of error control. A blocking factor, if chosen appropriately, can remove an identified source of variability from the experimental error term used to test treatment effect significance in an analysis of variance (ANOVA). Soil type provided the blocking factor in this generalized, randomized complete block experimental design.

Two sizable field research sites were obtained, each consisting of a distinct, relatively homogeneous block of soil. Soils of different composition respond differently to compactive effort. Since soil type was a condition and not a treatment, its effects were removed from the analysis of treatment effects via blocking.

A rye cover crop was chosen for investigation due to its common use in Virginia and its status as an integral component of sustainable cropping systems developed for the mid-Atlantic region (Ess et al., 1992a). The following ground cover treatments were included in each block in the field experiment:

- Live rye crop, intact
- Desiccated rye crop, intact
- Above-ground rye biomass removed
- Fallow - bare soil

The fallow treatment served as an experimental control. Inclusion of the rye treatment with above-ground biomass removed was intended to reveal the contribution of undisturbed plant roots to soil strength. The two treatments in which above-ground biomass was maintained were included to permit examination of load cushioning effects. One treatment, chemical desiccation of a standing cover crop, is practiced by farmers using certain conservation tillage crop production methods (Allmaras et al., 1991). The other involves mechanical manipulation of, and tracking upon, a growing cover crop. The treatment represents a new set of sustainable farming practices under development at Virginia Tech (Vaughan et al., 1992).

Research plots were established in 1992 at two locations on the Virginia Tech Whitethorne Research Farm. One set of plots was arranged on a terrace adjacent to the New River in a fine, mixed, mesic, Aquic Argiudolls ("McGary silt loam"). The level site had supported production of corn (*Zea mays*) grown for silage. The second set of plots was arranged on an upland site in a fine-loamy, mixed, mesic, Typic Hapludults ("Zoar loam"). The gently sloping site (1-2%) had not been cropped since 1990.

Five treatment replicates were established in each block. Replication allows the investigation of cover treatment-soil type interaction. Evidence of such interaction can provide valuable information in that one subset of treatments might be better for some conditions (blocks), while a different subset of treatments might be preferred in other conditions (Lentner and Bishop, 1993). Due to weather-related damage to a group of plots in the river terrace (McGary silt loam) block, only four replicates from each block were included in the experiment. The locations of experimental units, assigned randomly to areas within each block, are shown in Figures 4 and 5.

Two sets of soil core samples were taken from each experimental unit at each level of traffic. Four sets of soil core samples were taken from each experimental unit to establish initial, uncompacted conditions. Although this subsampling approach did not provide more degrees of freedom for hypothesis/significance testing, it produced more precise measures of soil properties, reducing the impact of sampling errors that were made but not noticed.

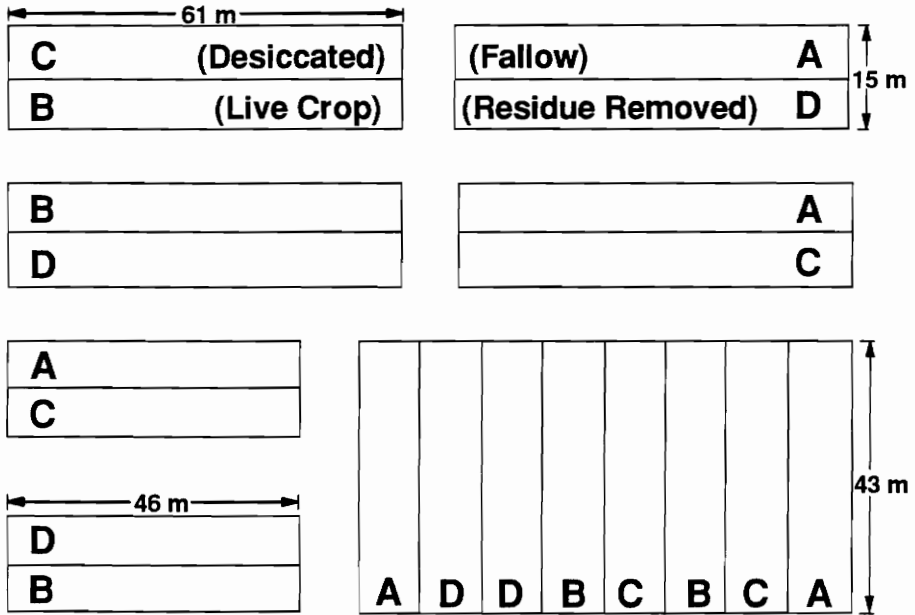
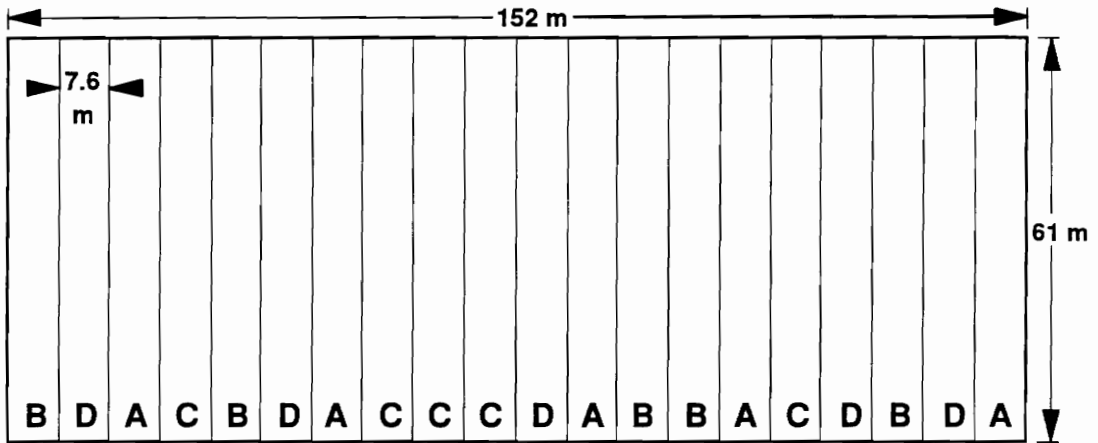


Figure 4. Locations of experimental units within the upland site on the Zoar soil (Block 1).



Legend: A = Fallow C = Desiccated B = Live Crop D = Residue Removed
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Figure 5. Locations of experimental units within the river terrace site on the McGary soil (Block 2).

Site Characterization Procedures

Detailed site descriptions, along with physical and chemical property data for the soil types within the field experiment boundaries, are provided in Appendix A. Physical property data, compiled in conjunction with Virginia Tech soil scientists, include particle-size distributions and bulk densities for each soil horizon. Chemical property data include organic matter content, pH, cation exchange capacity, and base saturation.

Soil samples were collected from randomly-selected locations within the experimental plots. Additional particle-size analyses (PSA's) for soil collected from the top 20 cm of the Ap horizons were performed by Virginia Tech Crop and Soil Environmental Sciences Department Soil Physics Laboratory personnel.

Further physical property characterization was conducted in Agricultural Engineering Department laboratories. Loose soil samples were collected and analyzed to determine the Atterberg (i.e. liquid and plastic) limits for the soils (Sowers, 1965). The consistency limits are indices of the behavior of artificial mixtures of soil and water as affected by moisture content (Figure 6). The limits, defined by the moisture contents required to produce specified degrees of consistency, are strictly empirical. A Casagrande's device (Jumikis, 1962) was used to determine the liquid limit (w_l), the dividing line between liquid and plastic states, for each of the two soil types.

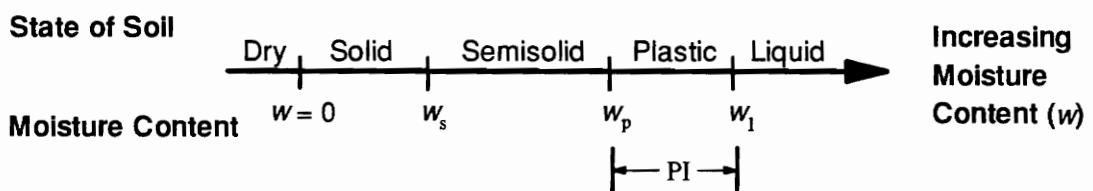


Figure 6. Atterberg limits and related indices (after Karafiath and Nowatzki, 1978).

The plastic limit (w_p), the dividing line between plastic and semisolid states, was identified in the laboratory as the lowest water content at which the soil could be rolled into threads 3.2 mm in diameter (Liu and Evett, 1990). Plastic limit determination is to some extent subjective and influenced by human factors. The almost universal acceptance of the Atterberg method has prevented the introduction of new, more objective methods, however (Karafiath and Nowatzki, 1978).

Compactibility is the maximum density to which a soil can be packed by a given amount of energy (Bradford and Gupta, 1986). The *Standard Proctor test* was performed in the laboratory to establish moisture-density relationships for each soil type (Burke et al., 1986). Samples were prepared for the range of moisture contents encountered in the field. Testing over the range of moisture contents produced a clearly-defined local minimum and maximum bulk density for each soil. Eleven samples were tested for the McGary soil and thirteen samples were tested for the Zoar soil. Polynomial regression was used to fit an expression of bulk density in terms of moisture content to each set of data.

Field Research Procedures

Field Operations: Field research plots comprised approximately one hectare at each location. The upland site, covered by a dense mat of growing vegetation and vegetative residues, was treated with Roundup® applied at a rate of 7 L/ha (glyphosate, 3.4 kg/ha) on October 12 and 13. Suppression of vegetative growth was attempted to ensure satisfactory cutting of the plant material with a disk harrow. Frost subsequent to herbicide application rendered the suppression approach ineffective, necessitating the burning of upland-plot-area vegetation. A controlled burn was performed on October 23 and 26. The river terrace plot area was spot treated with the herbicide to kill the few weeds that were present following the corn silage harvest.

The upland plot area was tilled with a V-frame subsoiler. The soil was penetrated to a mean depth of 33 cm on October 28. The lower plot area was tilled on the same day to a mean depth of 25 cm. Tillage depth means were determined from ten measurements at each site. Penetration depths were measured using the original, undisturbed soil surface as the datum plane.

Fertilizer was applied to the plot areas according to soil test recommendations from the Virginia Tech Soil Testing and Plant Analysis Laboratory. A bulk blend of granular

diammonium phosphate, muriate of potash, and urea was applied at a rate 33.6 kg N/ha, 67.3 kg P₂O₅/ha, and 67.3 kg K₂O/ha on October 30.

Following fertilizer application, all plots were disked three times with an offset disk harrow. Plots on the upland site were also tilled with a roller harrow before 0.9 cm of rain (Appendix B) halted field work. An additional 2.1 cm of rain fell over the next three days, October 31-November 2. All plots were disked for a final time with the offset disk harrow on November 11, after soil moisture conditions returned to favorable field working levels.

Rye was planted at a rate of 101 kg/ha on all cover-cropped plots on November 11. The drill used to plant the crop covered 18 rows spaced at 178 mm on center, producing a working width of 3.2 m.

Electric fencing was installed on November 12 and 13 to prevent tracking and subsequent random soil compaction by machine traffic and/or foraging deer. The 13-mm electric fence tape was arranged in a three-tier configuration. Two coplanar strands were positioned at heights of 30 and 120 cm on a series of wooden and fiberglass posts. A third strand, attached to a second set of posts at a height of 76 cm, was separated from the interior strands by a horizontal distance of 76 cm. The three-dimensional nature of the fence provided a psychological deterrent sufficient to prevent animal traffic within the

plots. A stand of "diversionary" rye, planted outside the fenced borders to satisfy the appetites of the voracious deer, was thoroughly tracked, however.

The plots were scheduled for an application of nitrogen fertilizer (78.5 kg N/ha) in late February. Untimely precipitation, including two 4-cm rainfall events in March, delayed top-dressing until late April. The second application of granular N fertilizer was completed with a walk-behind single-fan spreader on April 25. The application rate was reduced to 56 kg N/ha to lessen the potential for lodging (D.E. Brann, Professor, Department of Crop and Soil Environmental Sciences, Virginia Tech, private communication, April 1993).

Site Preparation: One third of the cover-cropped plots were desiccated with Gramoxone Extra® (3.2 L/ha; paraquat, 0.58 kg/ha) herbicide mixed with a surfactant on May 16. The herbicide, applied with a backpack sprayer, was allowed 14+ days to produce total cover-crop kill (Hagood et al., 1990). A five-percent solution of Roundup® herbicide mixed with a half-percent surfactant solution was spot applied, on an as-needed basis, to prevent weed growth on the fallow plots.

Traffic zones were selected to ensure the best possible level of rye yield/condition uniformity within each plot. The 15-m wide zones were marked prior to biomass sampling to facilitate the collection of representative samples and to guide foot traffic.

Biomass Sampling: Rye biomass was sampled on cover-cropped plots by removing all above-ground growth from three 0.20 m² quadrats per plot on May 20-21. Biomass samples were taken in close proximity to marked, planned tractor traffic zones. One sample was taken to represent each marked traffic lane. Samples were taken from each end and from the midpoint of a diagonal line spanning the width and breadth of the core sampling zone within each plot (Figure 7). The sampling arrangement permitted estimation of a biomass yield for each level of traffic within each cover-cropped plot. Biomass samples were weighed, dried at 54 °C until a constant weight was attained (at least 60 hours), and reweighed to determine yield and moisture content.

Biomass Sampling Map

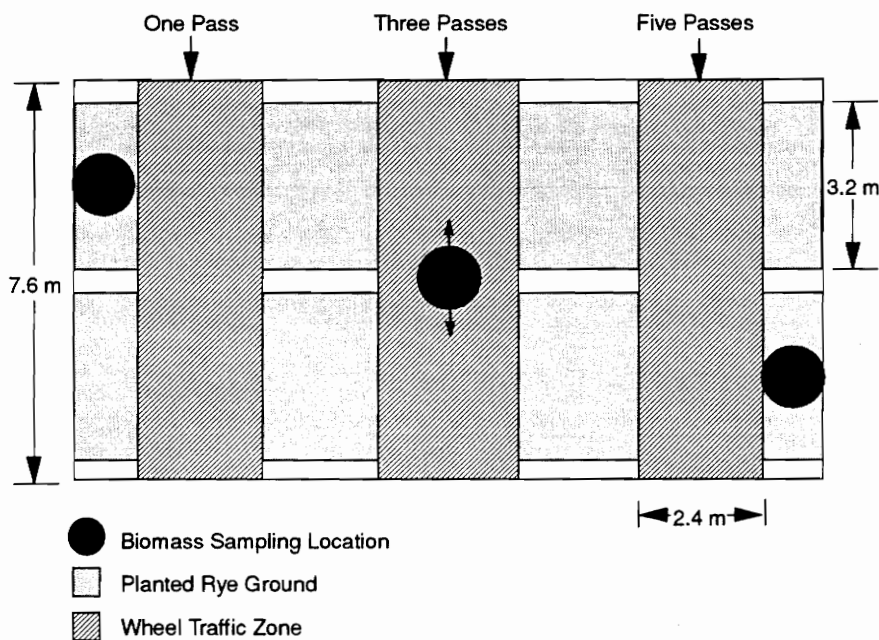


Figure 7. Original biomass sampling arrangement for the cover-cropped plots.

The first set of biomass samples indicated yield variability that did not appear to exist within some plots. For this reason, a second set of samples was collected from live crop and desiccated treatment plots after core sampling was completed. A rectangular steel frame (40 cm by 50 cm) was used to circumscribe sampling sites within the wheel tracks. Two 0.20-m² samples were taken from each traffic level within each plot. Since the sampling area was doubled and the sampling sites were more closely spaced, the second set of rye yield estimates was thought to provide a more accurate assessment of in-field conditions.

All above-ground biomass was taken from residue-removed plots over the May 21-24 period. Foot traffic lanes were established along the boundaries of each residue removed plot with a walk-behind, self-propelled sickle mower. Rye growing within tractor traffic lanes was cut with hand-held string trimmers and gently raked from the traffic zones. Care was taken to avoid foot tracking within tractor traffic lanes.

Tractor Specifications: The soil in the experimental plots was loaded by the passage of a Case-International Model 1594 two-wheel drive tractor. The tractor had the following specifications:

Vehicle Shipping Weight

• Front Axle Weight	1234 kg
• Rear Axle Weight	2336 kg
• Total Weight	3570 kg

Tires

• Rear - Goodyear "Traction Sure Grip", R-1, 6-ply	18.4 x 34
• Front - Goodyear "Super Rib Tractor", F-2, 8-ply	10.00-16

Dimensions

• Wheelbase	2540 mm
• Tread Width	1930 mm

The tractor was equipped with six front-mounted, cast iron weights. The rear tires were partially filled with liquid ballast. No actual draft loading was applied due to the difficulty of achieving realistic slippage values (Soane et al., 1981a) and to maintain undisturbed tractor wheel tracks. To simulate the dynamic weight transfer associated with drawbar loading and to provide additional ballast, a mounted implement was carried by the tractor three-point hitch. Ballast, including the mounted implement, was arranged to achieve a static weight distribution of approximately 20% on the front axle and 80% on the rear axle.

Static Vehicle Weight as Tested

• Front Axle Weight	1059 kg
• Rear Axle Weight	4842 kg
• Total Weight	5901 kg

A set of four portable scales was used to ensure that the tractor's weight was evenly distributed between the left and right wheels. The tractor lift arms were held in place by a set of steel wedges, installed to prevent the mounted implement from causing lateral weight shifts while the vehicle was in motion.

Tire inflation pressures were set at levels recommended by the tractor manufacturer for general field work conditions. The front tires were inflated to 193 kPa, the rear tires to 110 kPa. The mean pressure exerted by each tire on the soil surface was estimated by the following equation which assumed the contact area to be approximately the shape of an ellipse (Liljedahl et al., 1989):

$$p = \frac{W}{0.78bl}$$

where

p = mean soil pressure (kPa)

W = wheel load (kN)

b = maximum width of contact area (m)

l = maximum length of contact area (m)

Tire contact dimensions for the Case-International tractor were measured on a level concrete surface with the following results:

Front Tires

• Maximum Width of Contact Area	0.122 m
• Maximum Length of Contact Area	0.274 m
• Wheel Load	5.19 kN
• Mean Contact Pressure	199 kPa

Rear Tires

• Maximum Width of Contact Area	0.451 m
• Maximum Length of Contact Area	0.669 m
• Wheel Load	23.75 kN
• Mean Contact Pressure	101 kPa

The contact pressures, based on projected areas comprised of tire lug-concrete interfaces and inter-lug voids, agreed well with inflation pressures. Such measurements, taken under static conditions on a hard surface, serve as standard estimates of difficult-to-measure pressure distributions that exist in the field under varying soil surface and dynamic loading conditions.

The desire to simulate actual field working speeds was balanced by the necessity of accurately and precisely retracing wheel tracks in order to gauge multipass effects. With the engine operating at 1750 r/min, the tractor was driven at a nominal ground speed of 4

km/h. The travel speed, though slow by some standards, was within the range of normal field speeds for row crop production (ASAE, 1993a). It should also be noted that, in a study of wheel speed effects on soil compaction, Horn et al. (1989) used 4.5 km/h to represent *fast* tractor travel, with 0.7 km/h labeled *slow* and 8 km/h *very fast*.

Traffic Application: All plots were tracked at one time to ensure soil moisture content consistency across each level of machine passes. Sets of wheel tracks for the different traffic levels were separated by a distance of approximately 2.4 m to prevent contamination of zero-pass soil samples by wheel track compaction. Tracked and undisturbed soil zones were maintained by the traffic and sampling arrangement to preserve information from the soil at all traffic levels. The tractor was driven across the plots in the manner depicted in Figure 8.

Soil Core Sampling Map

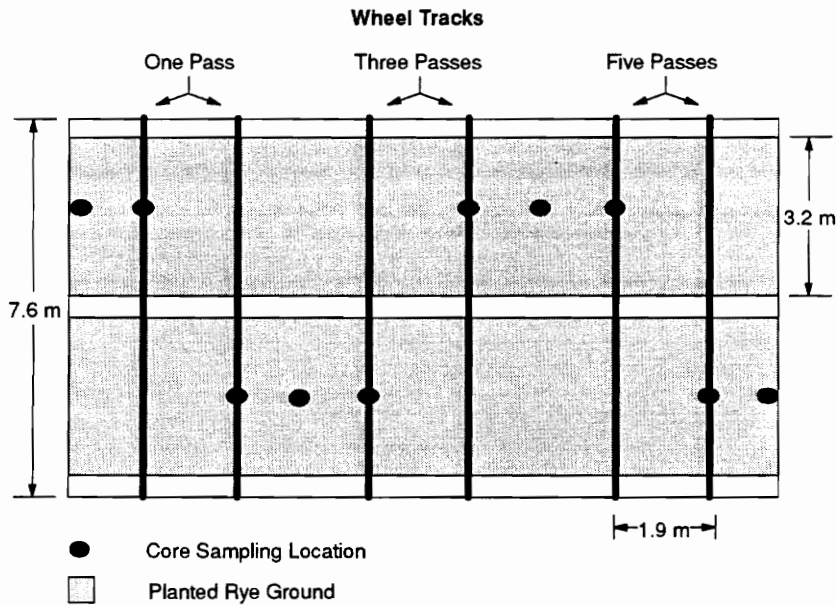


Figure 8. Tractor traffic and soil core sampling arrangement.

The soil in the research plots was thoroughly tilled prior to rye planting. Fencing was put in place to exclude even animal traffic subsequent to planting. The state of compactness of the soils made it reasonable to predict that the first machine pass would produce the greatest change in soil bulk density within the wheel tracks that were subjected to multiple passes. Additional traffic levels - three and five passes - were included in the experimental design with the intent of revealing differences in the soil response to multiple machine passes due to the various treatments. Inclusion of multiple machine passes also modeled realistic field conditions. According to Håkansson (1988), the total wheel-track area

covered by tractor and harvester traffic, **in one growing season**, averages 3.5 to 4 times total field area for conventionally-tilled small grains, corn, soybeans, or cotton.

Soil Moisture Content Sampling: Loose soil samples were collected from core sampling sites immediately after tracking. The moist samples were placed in sealed containers and transported to the laboratory for analysis. The samples were weighed to the nearest 0.001 g, oven dried at 105 ° C to a constant mass, then reweighed. The following equation was used to evaluate moisture content (Jumikis, 1962):

$$w = \frac{W_w}{W_s} \times 100$$

where

w = moisture content of soil (%)

W_w = weight of water in soil sample (g)

W_s = weight of oven-dried soil solids in sample (g)

The samples were used for the sole purpose of establishing moisture conditions at each core sampling site at the time of soil loading. Core sampling then proceeded as quickly as possible.

Soil Core Sampling: Core sampling is widely used, simple to accomplish, and can produce very accurate results (Soane et al., 1981a). The core method preserves a known volume of soil as it existed *in situ* (Erbach, 1987). Each soil core sample can provide the basis for bulk density, pore size distribution, and hydraulic conductivity testing, all in one aluminum cylinder. Rogers et al. (1985) compared four methods of acquiring saturated hydraulic conductivity data: small cores, auger hole, double-tube, and drawdown. They found that cores gave data equivalent to the other methods, and that 20 core samples could be processed during the same time as: a single drawdown, 5 auger holes or 1.25 double-tube tests.

Undisturbed core samples were collected during the period June 1-10 to assess changes in soil physical properties due to wheel traffic. Samples were taken at two depths. One cylindrical core, 5 cm in diameter and 5 cm in length, was taken from the 2.5 to 7.5 cm depth zone. Another core was taken from the same sampling site from the 15 to 20 cm depth zone. The first core represented surface compaction effects. The second core represented compaction effects from well into the primary tillage zone. The depth of the second sample was such that surface horizon properties of each soil were still represented, however.

Sampling depth was determined by two factors: 1) the anticipated depth of compaction resulting from row-crop tractor traffic, and 2) the desire to stay within the surface soil

horizon. The Case-International Model 1594, with its rear axle weight of less than 5 Mg, represents the average row-crop tractor used in Virginia (Ess et al., 1992b). Deep compaction is not typically associated with wheeled vehicles of the size used in this experiment (Burger et al., 1985; Voorhees et al., 1985). Soil horizons are identified by significant changes in soil properties, such as texture and structure, as one moves downward through a soil profile (Creggar et al., 1985). Property differences that permit demarcation of soil horizons can produce changes in soil behavior that might incorrectly be attributed to external forces such as compacting loads. For instance, Rogers and Carter (1987) showed that a 1-cm change in sampling depth could produce a tenfold change in measured saturated hydraulic conductivity in a layered soil. The Ap horizon of the McGary soil at Whitethorne Farm extends to mean depth 28 cm. The Ac horizon just below contains a much higher percentage of clay (Appendix A). For the Zoar soil, the Ap horizon extends to a depth of 25 cm.

Soil core samples were collected with a double-cylinder, hammer-driven core sampler (Blake and Hartge, 1986). Undisturbed soil samples were collected in aluminum liners (5.08 cm O.D, 4.83 cm I.D.). The 12.5-cm steel sampler body housed three aluminum liners: two that were 2.54 cm long and one that was 5.08 cm long. The 5.08-cm liner was positioned between the shorter liners. Only the soil collected within the 5.08-cm liner from each sampling depth at each site was retained for analysis. Soil within each 2.54-cm liner was discarded in an attempt to minimize any sampler-induced compaction effects. Any

soil retained within the sampler tip was also discarded. The soil sampler configuration is illustrated in Figure 9.

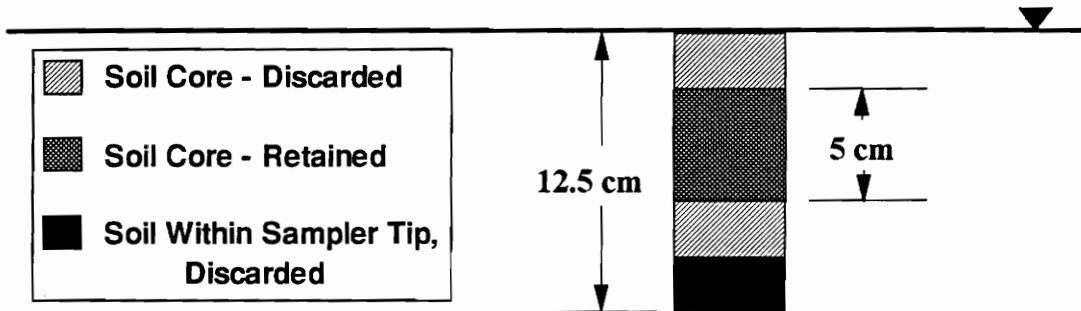


Figure 9. Soil core sample configuration within the hammer-driven core sampler body.

After the soil core sampler was extracted from a surface-zone sampling site, a finishing auger 7.6 cm in diameter was used to enlarge the core cavity, removing any loose soil and preparing the site for extraction of the subsurface core.

Soil core rejection criteria: Macropores visible at the soil surface were avoided when selecting core sampling sites. These preferential flow paths add considerably to water infiltration *in situ*, but do so at a much lower rate than if present in soil cores. In the soil, a surface-connected pore will fill quickly with water. If present in an extracted soil core, a continuous channel 5 mm in diameter can have a conducting efficiency 50 times that of the

same channel *in situ*. A 10-mm channel can produce conductivities two orders of magnitude greater in cores than in place in the soil (Jakobsen and Moore, 1981).

Cooke (1993a) classified preferential flow paths (macropores) based on the mode of formation and persistence within the soil. Biopores, formed as a result of the interactions between the soil and soil biota, were of particular importance in the root zone due both to size (> 10 mm in diameter) and stability. Such pores, typically connected to the surface, were easily avoided during sampling in uncompacted zones. Wheel traffic, however, tended to obliterate surface connections, making detection impossible until a core was extracted and examined. Cores with large continuous pores were discarded. Conductivities determined from such cores would have provided grossly inflated estimates of actual in-field values. Destruction of surface connections by wheel traffic would have produced further, significant reductions in the actual conductivity of such pores *in situ* (Edwards et al., 1979).

Soil cores containing rocks that protruded beyond core boundaries were discarded due to the clear potential for detrimental effects on handling, processing, and soil property measurement. Evidence of boundary irregularities, such as that manifested by core movement within an aluminum liner, was also sufficient cause to discard a core. Cores were collected in sets - surface plus subsurface - at a sampling site. If one core was rejected, both cores in a set were rejected.

A total of twenty cores were collected from each experimental unit or plot. Four core samples, two from the surface zone and two from the subsurface zone, were taken from the wheel tracks representing each of three levels of wheel traffic. Eight core samples, four from the surface zone and four from the subsurface zone, were taken from undisturbed soil zones adjacent to wheel track samples (Figure 8). Samples taken from undisturbed zones served as controls from which property differences (e.g. Δ bulk density and Δ capillary porosity) resulting from traffic were determined. The regular wheel track compaction patterns produced by the tractor-grain drill combination during cover crop establishment were evident and were avoided when core sampling was performed. Sealed core sample liners were labeled with specific location and depth information immediately after extraction. A total of 640 soil cores were collected and analyzed in the initial round of sampling.

Laboratory Analysis

Laboratory analysis of soil core samples included determination of dry bulk density, total soil porosity, soil microporosity, soil macroporosity, and saturated hydraulic conductivity. Soil samples were sealed with plastic caps immediately after collection and transported in cushioned containers to refrigerated storage. Samples were processed in batches of 20, beginning with a 24-hour saturation period. Laboratory analysis commenced with

saturated hydraulic conductivity testing, followed by pore-size distribution determination, and concluded with oven drying and dry bulk density measurement.

Saturation: Intact cores were saturated in a three-stage process. First, cores with the bottom plastic cap removed were inverted and placed in a soaking tray. The tray, lined with a coarse screen to ease water movement to the cores, was filled to a depth of 1 cm with tap water. A small hole in the plastic cap covering the soil core allowed tap water to enter the soil column and fill micropores by capillary action. This initial wetting stage prevented air from being trapped in pores by the subsequent saturation steps. The process was allowed to continue for 12 hours. Next, water was added to the soaking tray until it reached the highest level that avoided flooding the exposed soil core surfaces. The process continued for another 12 hours. Finally, soil core surfaces were flooded to ensure saturation immediately prior to hydraulic conductivity testing.

Hydraulic Conductivity: The saturated hydraulic conductivity (K_{sat}) of each intact soil core sample was determined by the constant head method (Klute and Dirksen, 1986). A hydraulic head difference was imposed on each intact soil core by a 25-cm column of water.

A saturated sample was taken from the soaking tray, the plastic lid removed from its upper surface, and a perforated lid lined with plastic mesh installed to cover its lower surface.

(The plastic mesh offered minimal resistance to water movement while preventing soil loss from the samples during testing.) The sample was then installed in a testing silo, or cylinder. The cylinder, consisting of a length of transparent polyvinyl chloride (PVC) pipe and a rubber transition coupling, was connected to a central reservoir. After a sample was installed in the testing apparatus, a control valve was opened to permit water to fill the cylinder to the desired level. A sample was allowed to drip into a catchment until the water column level stabilized.

After a steady-state flow condition was achieved, a flask was placed to receive water that percolated through the soil column. The mass of water that passed through the column was measured to the nearest 0.1g and recorded. The testing process was allowed to continue until a minimum of 100 g of percolate was collected. Elapsed times varied from two and one half minutes to 45 hours.

The hydraulic head difference imposed upon each soil core sample was measured to the nearest millimeter at least two times during conductivity testing. Slight fluctuations in the hydraulic head resulted from reservoir water level fluctuations necessary to actuate the automatic filler valve of the apparatus. The condition was addressed by using the mean of multiple head measurements in the calculation of saturated hydraulic conductivity. (The condition would probably have gone unnoticed had standard, opaque tubing been used.)

Appropriate conversions were made (e.g., mass to volume) and the values entered into the following equation to evaluate K_{sat} (Klute and Dirksen, 1986):

$$K_{sat} = \left(\frac{Q}{At} \right) \left(\frac{L}{\Delta H} \right)$$

where

K_{sat} = saturated hydraulic conductivity (cm/h)

Q = volume of water passing through the sample (cm³)

A = cross sectional area of soil core sample (cm²)

t = time (h)

L = length of soil core sample (cm)

ΔH = hydraulic head difference (cm)

Hydraulic Conductivity Apparatus: A constant-head apparatus for measuring the hydraulic conductivity of saturated soil samples was designed and constructed to facilitate the completion of this research. The basic design of the apparatus was suggested by a diagram and description given in Klute and Dirksen (1986). Suggestions for refinement of the Klute and Dirksen design were provided by Dr. James A. Burger, Professor of Forestry at Virginia Tech. Dr. Burger had built the conductivity apparatus used in the Virginia Tech Forest Soils Laboratory.

Innovative aspects of the apparatus constructed in the Agricultural Engineering Department included the use of transparent PVC tubing and friction-fit, rubber transition couplings. Use of transparent pipe allowed much easier measurement of water levels in the cylinders than did the use of standard PVC. The development of friction-fit rubber sleeves allowed rapid insertion and removal of soil cores, without the need for clamps, while providing leak-free operation. The apparatus, built around a 114-L reservoir, capable of handling 12 soil cores simultaneously, is depicted in Figures 10 and 11.

Constant-Head Conductivity Apparatus

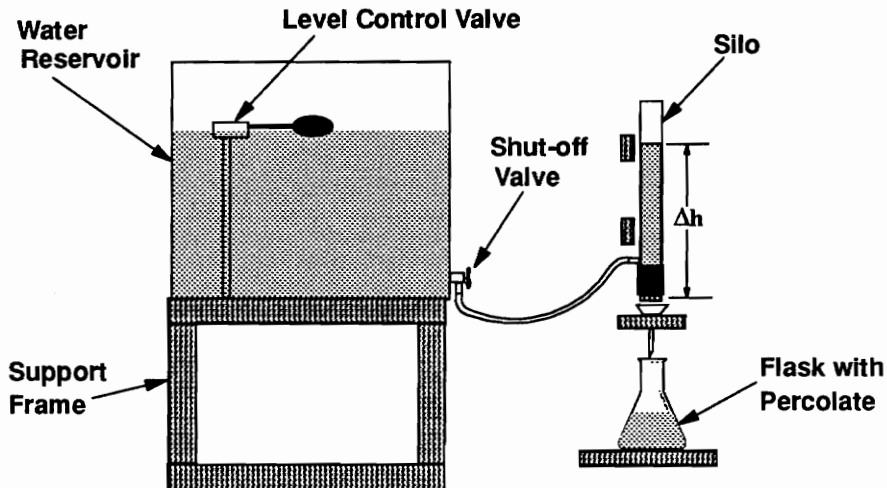


Figure 10. Diagram of the constant-head apparatus for hydraulic conductivity measurement.

K_{sat} Cylinder Assembly

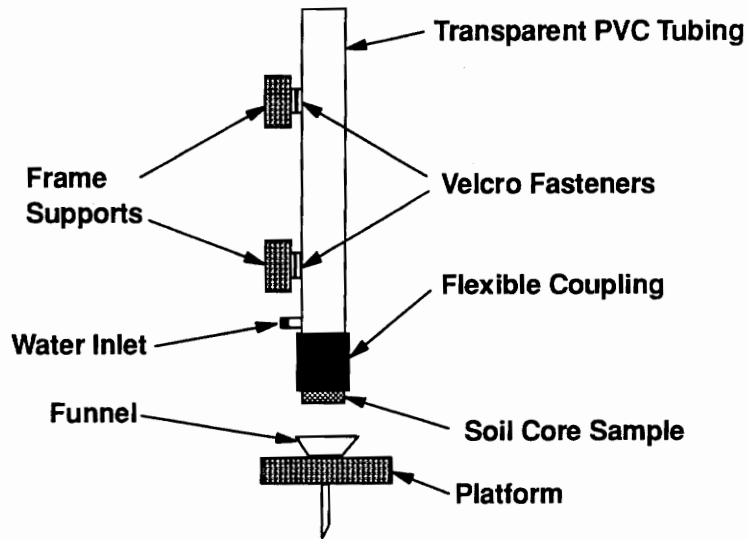


Figure 11. Hydraulic conductivity apparatus cylinder, detail view.

Soil Porosity: Saturated soil cores were removed from the hydraulic conductivity apparatus and allowed to drain by gravity for 15 to 30 minutes. The drainage period served to stabilize the saturated cores, preventing soil loss, and/or core slippage, upon removal of the perforated plastic caps. The cores were then ready for placement on the tension table.

The tension table procedure permitted determination of capillary and noncapillary porosity by evacuating soil macropores (> 0.06 mm in diameter) with a 50-cm water column. The

water column was used to create a negative pressure on an airtight porous surface. A 50-cm column created a suction, or tension, of 4.9 kPa which induced water movement from soil pores of radii greater than r . Pore radius was determined by the following *capillary rise* equation (Hillel, 1971):

$$h = \frac{2\gamma\cos\phi}{\rho gr}$$

where

h = height of capillary rise = height of water column (cm)

γ = surface tension of water (approximately 72.7 g/s² at 20 °C)

ϕ = the wetting angle (normally taken as 0)

ρ = density of water (approximately 1 g/cm³)

g = acceleration due to gravity (approximately 981 cm/s²)

r = radius of capillary tube (soil pore) (cm)

The key component of a tension table apparatus is a membrane that conducts water at a reasonable rate, but when wet, is impermeable to air over the pressure range in which it is used (Vomocil, 1965). For this experiment, the membrane consisted of a double layer of Cosmos blotter paper placed over a layer of plastic mesh screen. The membrane was capable of holding the desired tension for several days. A membrane was replaced when its entire exposed surface had been covered one time by soil cores.

Tension Table Apparatus: A tension table was designed and constructed to facilitate the completion of this research. Principles of operation were outlined by Vomocil (1965). The actual apparatus was modeled after a tension table used in the Virginia Tech Forest Soils Laboratory. Thorough sealing and a level table surface are critical elements of successful tension table operation. The table outperformed the original due to better sealing at the table-outlet interface achieved by threading a plastic nipple directly into a thicker, more rigid Lexan® table surface. The apparatus is depicted in Figures 12 and 13.

Tension Table Apparatus

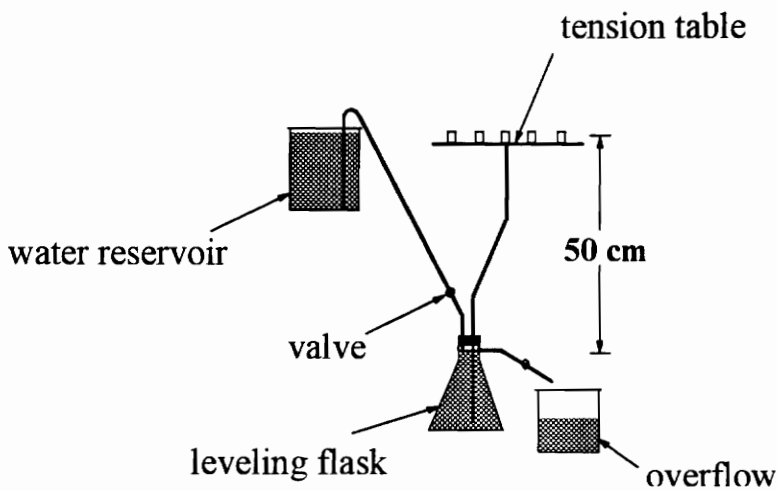


Figure 12. Illustration of the tension table arrangement.

Tension Table Detail View

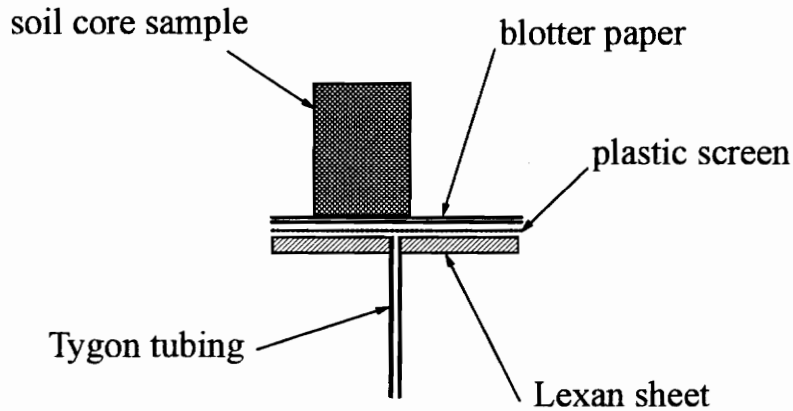


Figure 13. Depiction of the tension table surface during operation.

The tension table reservoir supplied water to flood the table surface during the startup procedure, when the blotter paper layers were initially saturated. The edges of the paper extended beyond those of the plastic screen to permit sealing. The blotter paper was rolled to remove air trapped beneath it, then the table was drained into the overflow container via the leveling flask. Draining surface water from the table sealed the blotter paper to the Lexan surface and prepared the table for operation. The water column, measured from the center of a soil core to the leveling flask outlet, was fed by water drained under tension from the soil cores. A small flow of water was maintained between the reservoir and the leveling flask to replenish net evaporative losses from the blotter paper surface and maintain a constant water column height. The tension table was

covered to minimize evaporation during the 24-hour periods over which sets of cores were allowed to reach equilibrium. The weight of each soil core at equilibrium was then recorded to the nearest 0.1 g.

Bulk Density: The final laboratory procedure was dry bulk density determination. Intact soil cores within sampler liners were oven dried at 105°C to a constant weight (Blake and Hartge, 1986). The drying process took an average of 24 hours to complete. Each soil core sample within a sampler liner and an aluminum drying container was weighed to the nearest 0.1 g. Soil cores were removed from sampler liners and placed into numbered, sealed containers for storage. Liners and drying containers were then weighed to determine the net weight of each dry soil core.

The following formulae were used to quantify soil bulk density and pore size distribution:

$$BD = \frac{ODW}{V}$$

$$TP = \frac{PD - BD}{PD} \times 100$$

$$CP = \frac{EW - ODW}{V} \times 100$$

$$NCP = TP - CP$$

where

BD = dry bulk density (g/cm³)

ODW = oven-dry weight of soil (g)

V = inner volume of a soil core sampler liner (cm³)

TP = total porosity (%)

PD = average particle density (2.65 g/cm³)

CP = capillary porosity (%)

EW = weight of soil at equilibrium (g)

NCP = noncapillary porosity (%)

Density of water = 1 g/cm³

Statistical Analysis

Statistical Model: The following linear model provided the basis for explanation and analysis of experimental observations:

$$y_{ijkm} = \mu + \tau_i + \rho_j + (\tau\rho)_{ij} + \varepsilon_{ijk} + \delta_{ijkm}$$

where

y_{ijkm} = experimental observation, variable of interest

μ = overall mean, a constant

τ_i = treatment effect due to the i^{th} treatment ($i = 1, 2, 3, 4$)

ρ_j = block effect due to the j^{th} block ($j = 1, 2$)

$(\tau\rho)_{ij}$ = block-treatment interaction term

ϵ_{ijk} = experimental error term ($k = 1, 2, 3, 4$)

δ_{ijkm} = subsampling error term ($m = 1, 2$ or $m = 1, 2, 3, 4$)

Experimental observations of bulk density, porosity, and hydraulic conductivity were produced by analysis of soil core samples. Analysis of treatment effects was performed for each of two soil sampling depths and four levels of machine traffic. Surface and subsurface effects were analyzed and results reported separately. Separate analyses were performed for each level of machine traffic. Comparisons of treatment means were based on information derived from ANOVA reports of the form illustrated in Table 1:

Table 1. ANOVA for the Generalized RCB Design with Subsampling.

<i>Source</i>	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>EMS</i>
Blocks	r-1	SSB	MSB	—
Treatments	t-1	SST	MST	$\sigma_{\delta}^2 + s\sigma_{\epsilon}^2 + rsm\kappa_{\tau}^2$
Interaction	(r-1)(t-1)	SS(BxT)	MS(BxT)	$\sigma_{\delta}^2 + s\sigma_{\epsilon}^2 + sm\kappa_{\tau}^2$
Experimental Error	rt(m-1)	SSE	MSE	$\sigma_{\delta}^2 + s\sigma_{\epsilon}^2$
Subsampling Error	rtm(s-1)	SSS	MSS	σ_{δ}^2
Total	rtms - 1	SSY		

where

Source = source of variation

r = number of blocks

df = degrees of freedom

t = number of treatments

SS = sum of squares

m = number of replications

MS = mean squares

s = number of subsamples

EMS = expected mean squares

Significance Testing: Analysis of variance output was used to test the hypothesis that cover-cropped treatments affected soil response to machine traffic. The statistical hypotheses were framed as follows:

H_0 : All treatment means are equivalent

The previous hypothesis, stated in terms of the statistical model was

H_0 : All $\tau_i = 0$

With the null hypothesis that all treatments effects were equal to zero, the alternative hypothesis was that some treatments effects were not zero.

Significance testing of treatment effects and block-treatment interaction was conducted by comparing the appropriate source mean square to the experimental error mean square. The test statistic for the null hypothesis regarding treatment effects was

$$F = MST / MSE,$$

which follows the F distribution with $(t-1)$ and $rt(m-1)$ degrees of freedom.

The test statistic for block-treatment interaction was

$$F = MS(B \times T) / MSE,$$

which follows the F distribution with $(r-1)(t-1)$ and $rt(m-1)$ degrees of freedom.

The F statistics were used to determine significance levels, providing evidence in favor of either rejection, or failure to reject, the appropriate null hypothesis. Significance testing requires the conscientious experimenter to select an acceptable margin for error in rejecting a null hypothesis when in fact it is true (a Type I error) *prior to analysis of experimental results*. The experimenter's selection of this margin for error, or alpha level, has clear implications for altering conclusions drawn from experimental data. Alpha level selection has produced some controversy as a result. Voorhees (1991), in a discussion of

soil compaction significance, pointed out the trend away from the long-held rule that differences between treatment means must be statistically different at the 95% confidence level to be statistically significant. He argued that the trend follows recognition among researchers "that in a real farming situation, seldom are operations done with 95% confidence that the desired effect will be achieved." An alpha level (α) of 10% was adopted for this study of soil compaction.

Mean Separation Procedures: If significant differences were shown to exist among treatment means, separation procedures were used to determine which means were different. Fisher's Least Significant Difference (LSD) mean separation procedure was used to make multiple comparisons among the treatments. If used only when the basic ANOVA shows significantly different means, Fisher's procedure produces what is termed either a "protected LSD" (Lentner and Bishop, 1993) or an "F-protected LSD" (Sullivan, 1990). For each comparison of a pair of treatment means, the probability of a Type I error is fixed at a specified value of α — in this case $\alpha = 0.10$.

Fisher's LSD was used to indicate significant differences among treatment means for each variable of interest at each level of machine traffic. Surface and subsurface analyses were performed separately.

Another post-ANOVA procedure for comparing treatment means is the use of *linear contrasts* (Ott, 1988). A contrast is simply a linear combination of means whose coefficients sum to zero. Contrasts allow construction of more general mean comparisons as dictated by treatment structure and research objectives (Lentner and Bishop, 1993). In this experiment, comparisons could be made between treatments with root reinforcement and the one without. Likewise, treatments with above-ground biomass could be compared to those without. Significance for a contrast is calculated from a t-test (Hintze, 1990).

Saturated Hydraulic Conductivity Data Analysis. Saturated hydraulic conductivity data are treated as log-normally distributed in practice (Heard et al., 1988; Rogers et al., 1991; Jabro, 1992; Cooke, 1993a). K_{sat} values are greater than zero and can take on extreme values due to flow through macropores. ANOVA tests are robust with respect to departures from normality and mild departures from equal population variances. However, when two treatment means vary by a factor of two or more, the assumption of variance homogeneity becomes suspect (Mead and Curnow, 1983). Measured saturated hydraulic conductivities have been found to exhibit 25-fold differences **between replicates** (Ahuja et al., 1989). For data that are log-normally distributed, the variance is proportional to the square of the mean (Ott, 1988).

For the reasons discussed above, analysis of K_{sat} data typically requires the use "non-standard" analytical techniques. There are two basic approaches to analyzing K_{sat}

data. One is to transform the data prior to ANOVA testing. The other approach is to analyze K_{sat} data using nonparametric methods that are insensitive to the magnitudes of differences among treatments.

Geometric means (Heard et al., 1988) and logarithms (W.J. Edmonds, Associate Professor, Department of Crop and Soil Environmental Sciences, Virginia Tech, private communication, March 1994) have been used to transform saturated hydraulic conductivity data to decrease nonnormality. Transformation by either method reduces the effect of extreme, upper-tail values from log-normally-distributed data on mean squares in the analysis of variance. Log transformation of data permits the use of previously-discussed ANOVA techniques. Results must be presented on the transformed scale, however, complicating interpretation (Mead and Curnow, 1983).

Alternative Statistical Model for Saturated Hydraulic Conductivity: The subsampling approach used in this experiment provided the opportunity to calculate geometric means to represent K_{sat} values from each experimental unit. Pooling subsamples into geometric means necessitated the use of a different statistical model than was used for bulk density and porosity data analysis. The following linear model for a generalized RCB design was appropriate to explain saturated hydraulic conductivity response:

$$y_{ijk} = \mu + \tau_i + \rho_j + (\tau\rho)_{ij} + \varepsilon_{ijk}$$

Comparisons of K_{sat} means were based on information derived from the standard ANOVA for a generalized RCB design without subsampling (Table 2). As in the analysis that included subsampling, F statistics were computed by dividing MST and MS(BxT) terms by the mean square error term.

Table 2. ANOVA for the Generalized RCB Design.

<i>Source</i>	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>EMS</i>
Blocks	r-1	SSB	MSB	—
Treatments	t-1	SST	MST	$\sigma_{\epsilon}^2 + m\kappa_t^2$
Interaction	(r-1)(t-1)	SS(BxT)	MS(BxT)	$\sigma_{\epsilon}^2 + m\kappa_t^2$
Experimental Error	rt(m-1)	SSE	MSE	σ_{ϵ}^2
Total	rtm - 1	SSY		

K_{sat} Data Analysis Using Nonparametric Methods: Nonparametric methods require few assumptions about the populations from which data are obtained. There is no assumption of normal distribution. Procedures associated with Friedman rank sums are insensitive to the magnitudes of differences among treatments. The evaluation of treatment performance is based on ranks of treatment means within blocks. Consistency in ranking between, or among, blocks translates into significant differences among

treatments. The Friedman two-way layout test is used to perform nonparametric analysis of randomized block experiments (Hollander and Wolfe, 1973). The Friedman test is the nonparametric, distribution-free, analog of the parametric two-way RCB analysis of variance F-test (Hintze, 1990). The procedure is used to test the null hypothesis of no differences among treatments.

Saturated hydraulic conductivity data from this experiment were pooled to produce one mean per treatment per block prior to analysis. Treatment means were ranked for each block and the ranks summed across blocks. The following formula was used to compute a test statistic.

$$S = \left[\frac{12}{nk(k+1)} \sum_{j=1}^k R_j^2 \right] - 3n(k+1)$$

where

n = number of blocks

k = number of treatments

R_j = sum of ranks (over the n blocks) for treatment j

The test statistic was used to determine an upper tail probability for the null distribution of Friedman's S statistic (Hollander and Wolfe, 1973). If the probability was less than the

alpha level chosen for this experiment, $\alpha = 0.10$, means were declared significantly different.

It is worth noting that for an experimental layout with four treatments and two blocks, only eleven different values for the S statistic are possible, and only one produces significance ($S = 6$, $p = 0.042$). In other words, treatments must maintain the same ranking for both blocks in order for the Friedman procedure to detect significant differences among treatments, regardless of differences in the magnitudes of means. Statistical computing packages such as Number Cruncher and Minitab use a chi-square approximation technique to determine significance levels for Friedman tests. The approach produces errors for small-sample-number cases (such as a 4×2), and must be corrected by referring to tabulated S-statistic values.

Multiple comparisons were made among treatment pairs based on the absolute difference between the sums of ranks received by the treatments. For k treatments, there are $k(k - 1)/2$ absolute differences $|R_u - R_v|$, $u < v$, that can be calculated. If the absolute difference for a pair of treatments exceeded a critical value (Hollander and Wolfe, 1973), the treatments were declared significantly different.

Results and Discussion

The experiment produced measurable results that translated into statistically- and physically-significant differences among the treatments. The experimental design, which included blocking, replication, and subsampling proved quite effective. The blocking factor accounted for a large portion of the variability measured in many of the analyses — variability that would otherwise have inflated the experimental error term. Replication revealed no significant block-treatment interaction. This result was meaningful in that the treatments behaved consistently across the soil types. The soils, though separated by a small distance, were quite different. The McGary soil contained over 50 percent more clay in the surface horizon than the Zoar soil (Table 3). Rock fragments were present on and about the surface of the Zoar soil, typifying much of the upland acreage on the Whitethorne Farm. The soil of the river terrace, though poorly drained, produced noticeably higher biomass yields than its upland counterpart (Tables 6-7). Subsampling enhanced the precision of measurements made within experimental units on both soils.

Unless otherwise indicated, all of the statistical tests referenced in this chapter were performed on a personal computer. The primary software tool was the Number Cruncher Statistical System™ (Hintze, 1990; Hintze, 1992a,b). Certain nonparametric tests were performed using Minitab® Release 9 for Windows (Minitab Inc., 1993).

Soil Parameters

Particle-size distribution data for samples collected from the surface horizon of the McGary silt loam and the Zoar loam soils are presented in Table 3.

Table 3. Particle-size distribution data for the surface horizon (0-20 cm) of the Zoar and the McGary soils.

Component	Soil Type	
	Zoar	McGary
	g/kg	
Sand	381	339
Silt	495	468
Clay	124	193

The Atterberg limits and the plasticity index (PI) are presented for each soil in Table 4. The higher clay content of the McGary soil is reflected in the higher moisture contents necessary to produce plastic and liquid behavior in the soil, and in the greater plasticity index.

Table 4. Atterberg limits for the Ap horizon of the Zoar and the McGary soils.

Characteristic	Soil Type	
	Zoar	McGary
	% moisture content ($w_{\text{water}}/w_{\text{dry soil}}$)	
Plastic Limit	20.9	25.0
Liquid Limit	24.9	30.3
Plasticity Index	4.0	5.3

Regression results for the Proctor test data for the two soils are illustrated in Figures 14 and 15. The peak of each curve, representing the local maximum measured bulk density, defined the *optimum soil moisture content* for compaction of each soil. The McGary soil, with its higher surface-horizon clay content, produced a lower maximum bulk density at a higher optimum moisture content than the Zoar soil.

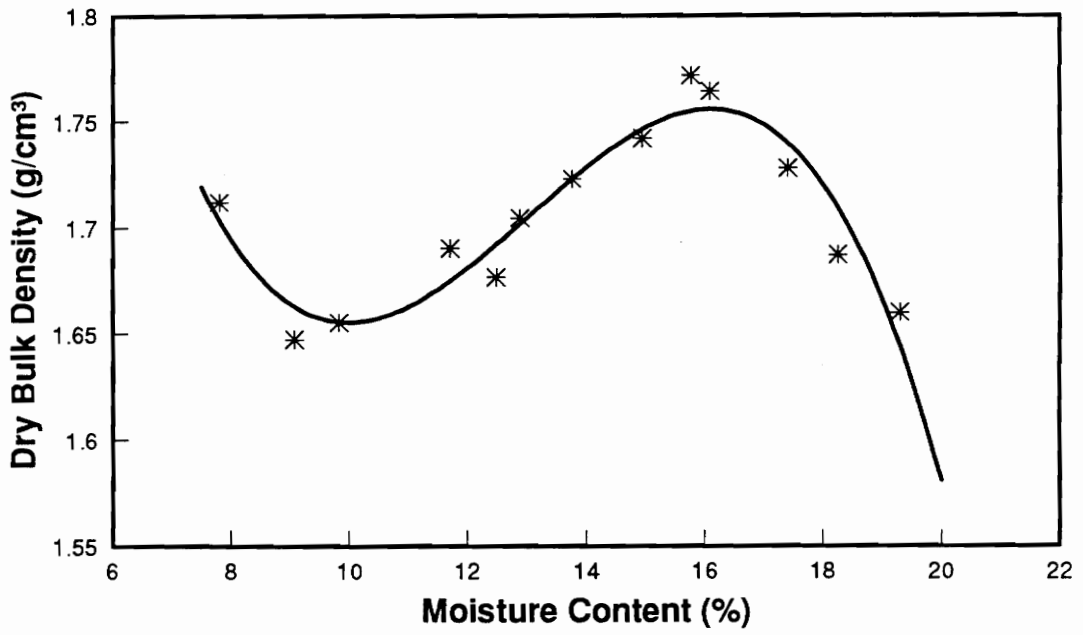


Figure 14. Data points from the Proctor test and the fitted regression line for the Zoar soil (Block 1).

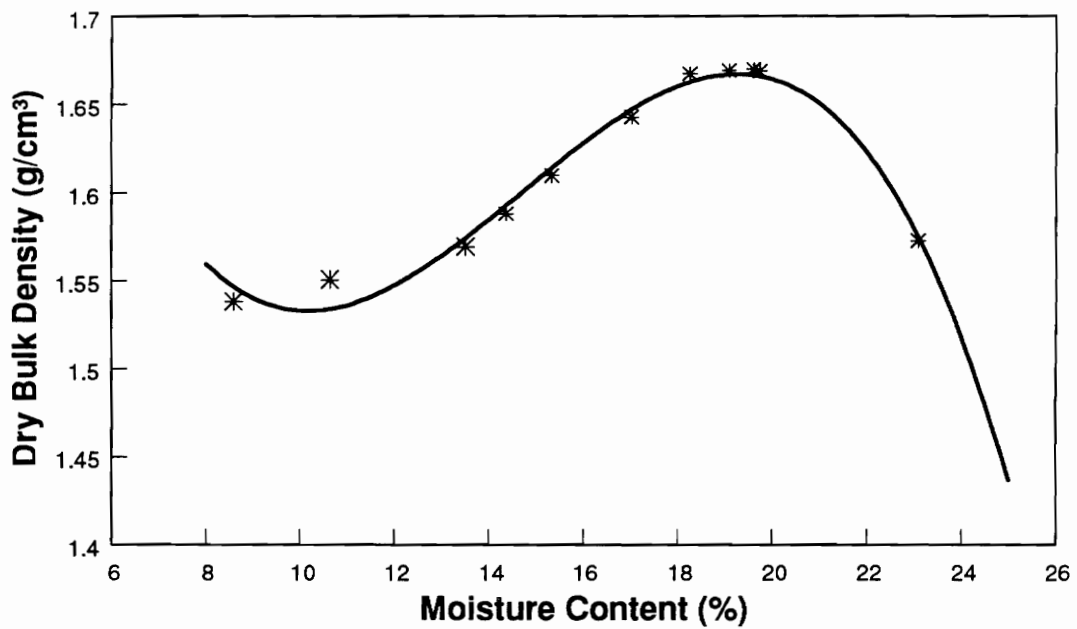


Figure 15. Data points from the Proctor test and the fitted regression line for the McGary soil (Block 2).

The following expressions describe the fitted regression lines:

Zoar Soil: $BD = 3.341 - 0.4253MC + 0.03449MC^2 - 0.000881MC^3$

McGary Soil: $BD = 2.413 - 0.2103MC + 0.01581MC^2 - 0.000359MC^3$

where

BD = dry bulk density (g/cm³)

MC = soil moisture content (%)

Proctor test results, compiled to aid interpretation of field experiment results, are summarized in Table 5.

Table 5. Standard Proctor test results for the Ap horizon of the Zoar and McGary soils.

Characteristic	Soil Type	
	Zoar	McGary
Maximum Dry Density (g/cm³)	1.76	1.67
Optimum Moisture Content (%)	16.1	19.2

Cover Crop Biomass Yields

Rye biomass yield results are presented in Tables 6-8. Each table provides yield means, the range of measured yields, and the coefficient of variation associated with treatment yields for each soil type. Mean 1 represents results from the first round of sampling; Mean 2 represents the second round. The estimated coefficient of variation, a measure of variability, was calculated by dividing the standard deviation of a set of yields by the mean yield (Law and Kelton, 1991).

Table 6. Rye biomass dry matter yield data for the live crop treatment.

Dry Matter Yield (Mg/ha)	Live Crop	
	Zoar	McGary
Mean 1	5.68	6.57
Range	2.30 - 9.30	3.55 - 10.40
Coefficient of Variation	0.28	0.28
Mean 2	3.93	6.27
Range	3.25 - 4.65	4.03 - 8.68
Coefficient of Variation	0.09	0.25

Table 7. Rye biomass dry matter yield data for the desiccated treatment.

Dry Matter Yield (Mg/ha)	Desiccated	
	Zoar	McGary
Mean 1	3.89	5.33
Range	1.75 - 7.65	2.70 - 9.65
Coefficient of Variation	0.43	0.38
Mean 2	2.99	4.65
Range	2.33 - 4.08	3.73 - 5.93
Coefficient of Variation	0.17	0.16

Table 8. Rye biomass dry matter yield data for the residue-removed treatment.

Dry Matter Yield (Mg/ha)	Residue-removed	
	Zoar	McGary
Mean	5.54	6.75
Range	4.00 - 7.50	1.80 - 10.50
Coefficient of Variation	0.22	0.33

Cover crop biomass yield means were higher for the plots established on the McGary soil than for those on the Zoar soil. The McGary site, though more poorly drained than the upland site, produced a noticeably better crop. The yield means measured from the second round of samples were lower than Mean 1 values, possibly reflecting some deterioration of the plant material. The measured ranges were less extreme, however, producing less variability among yield estimates, and closer agreement with perceived yield ranges.

Soil Moisture Content

As indicated in the literature and by Proctor testing, soil moisture content affects soil response to compactive effort. Moisture content (MC) was measured at each sampling site with the prospect of using it as a covariate. Certain conditions had to be met, however, before the appropriateness of this approach could be established. A fundamental

precondition for analysis of covariance is that treatment factors must not affect the values of the covariate (Lentner and Bishop, 1993). If such a condition exists, it is not possible to fully separate treatment and covariate effects in an analysis of covariance. As can be seen in Tables 9 and 10, the treatments did affect soil moisture content. Data for the surface zone (0-10 cm) of each soil are presented in Table 9. Data for the subsurface zone (10-20 cm) are presented in Table 10. Results of analysis of variance and Fisher's LSD procedure are indicated by letters following the mean values for each treatment within a soil type.

Table 9. Surface zone soil moisture content means (%).

Treatment	Soil Type	
	Zoar	McGary
Fallow	16.0 a*	18.0 a
Live Crop	12.1 b	16.6 b
Desiccated	14.8 a	18.8 a
Residue-removed	13.0 b	16.2 b

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$.

Table 10. Subsurface zone soil moisture content means (%).

Treatment	Soil Type	
	Zoar	McGary
Fallow	16.3 a*	21.2 a
Live Crop	10.3 c	16.3 d
Desiccated	13.7 b	19.1 b
Residue-removed	12.4 b	17.6 c

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$.

Soil in the surface zone of the fallow and desiccated treatment plots was significantly more moist than soil in the live crop and residue-removed plots for both soil types. On the upland site, soil moisture content means were lower in the subsurface zone than in the surface zone for all cover-cropped treatments. The live crop treatment produced the lowest subsurface MC means on both soils, while the fallow treatment produced the highest means.

There was no assurance that the different ground cover conditions would produce consistent moisture content values across the four treatments or between the two sampling depths. The potential for soil moisture losses resulting from evaporation and/or transpiration clearly differed among the treatments. One need but look at the rainfall

amounts that preceded soil core sampling and consider the factors in the moisture balance for each treatment to explain MC differences among the treatments. As seen in Table 11, the March 1993 precipitation amount at Whitethorne far exceeded the long-term average for the Montgomery County-Radford City area (Virginia Cooperative Extension Service, 1987). By late May, however, field conditions were becoming quite dry. The Whitethorne Farm received only 1.2 cm of rainfall from May 15 through May 30. It was only after a 0.76-cm rain (Appendix B) that soil tracking and soil core sampling commenced. By waiting for rain, and allowing time for it to infiltrate, it was hoped that some degree of moisture content uniformity could be achieved.

Table 11. Spring precipitation data for Whitethorne Farm, Montgomery County Virginia (cm) .

Month	Precipitation	
	1993	Average, 1941-1970
March	16.64	8.24
April	7.44	7.20
May	5.99	8.42
June	7.21	8.55

Until May 16, the date on which desiccated treatment plots were sprayed, the moisture content conditions on cover-cropped plots within each block should have been relatively

uniform. The paraquat herbicide treatment produced visible effects on crop status after one day. Following biomass removal on May 21 - 24, the three cover-cropped treatments subjected the soil to distinctly different drying conditions. The live crop continued to extract and transpire soil water to the atmosphere, but its above-ground presence limited evaporation from the soil surface. Uptake by the desiccated crop was minimal after May 17, and the crop residue limited evaporation. The residue-removed plots, of course, had no residue canopy and were subject to higher evaporative losses than the other cover-cropped plots.

Is it reasonable to assume that cover crops, growing, dead, or dying, will ever fail to affect moisture content? The answer is clearly *No*. Crop residues have been shown to increase soil moisture content by reducing evaporative water loss (NeSmith et al., 1987; Hulugalle and Palada, 1990). Live cover crops are typically suppressed with herbicides prior to planting primary crops. Suppression is done, in part, to reduce competition for moisture at a critical juncture in the primary crop production scenario. The farmer's field working and planting decisions are driven, to a great extent, by soil moisture conditions. There must be the presence, or prospect, of adequate moisture for seed germination and plant emergence.

The lack of moisture content uniformity in the field, though adding a degree of complexity to the interpretation of research results, mirrored conditions faced by farmers. To support

this contention, two questions must be answered. *Were the fallow plots at a reasonable moisture content for planting?* and *Was the "wait for rain, then proceed" approach reasonable for the cover-cropped plots?* The answer to both questions is *Yes*.

Soil physical properties responded to interactions of soil moisture content and soil cushioning/strengthening effects. Moisture content distribution information combined with Proctor moisture-density relationships for each soil type provided a critical analytical tool for separation of treatment and moisture effects, in lieu of a formal analysis of covariance.

The distribution of moisture content data for each treatment is shown in box plots (Figures 16 and 17). Each box plot is defined in terms of percentiles of the moisture content distribution. The bottom and top edges of each box are formed by the 25th and 75th percentiles, respectively. The line across the middle of each box is at the median (50th percentile). The upper and lower vertical lines are bounded by the 90th and 10th percentiles, respectively. The lengths of the vertical lines relative to the box show how stretched the tails of the distribution are (Hintze, 1990). The small circles represent the most extreme data points.

The figures are marked to indicate physically-significant moisture content levels. This method of presentation helps illustrate the potential for the moisture content distributions

produced by the treatments to affect soil response to machine traffic. The dashed horizontal line spanning the frame of each figure denotes the optimum moisture content of each soil for greatest compactibility as determined by the standard Proctor test. The solid line spanning the frame in Figure 16 represents the moisture content at which the Zoar soil was the least compactible.

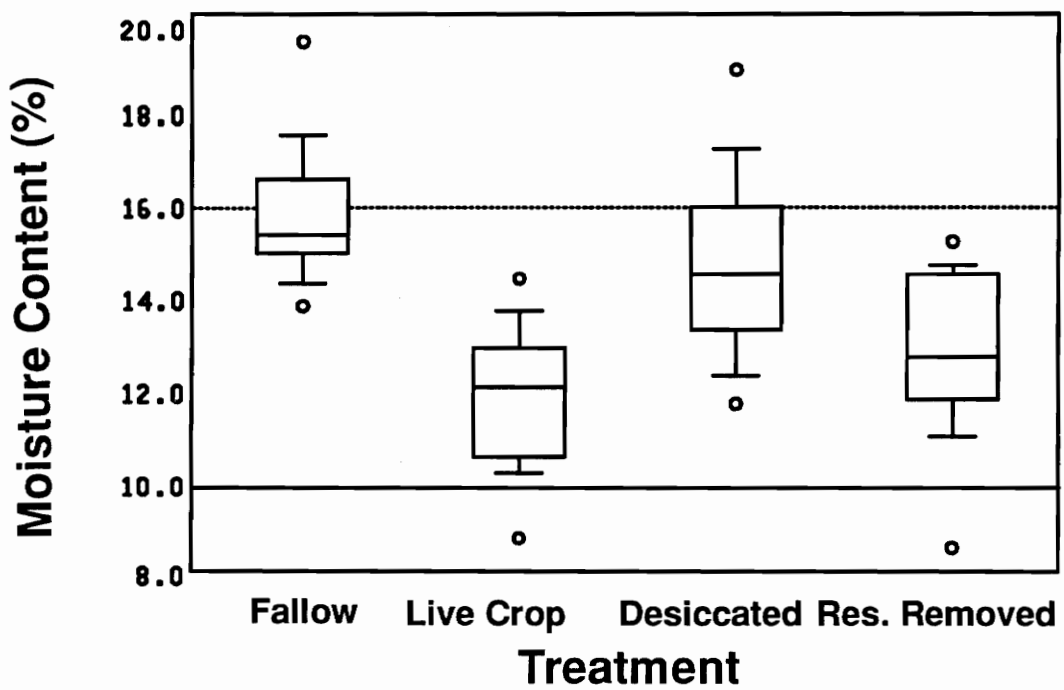


Figure 16. Moisture content box plots for the surface zone (0-10 cm) of the Zoar soil (Block 1).

The median moisture content of fallow plots in Block 1 was the highest among the treatments, and close to the optimum moisture content of the Zoar soil. The 75th percentile of the desiccated treatment's moisture content distribution was approximately equal to the soil's optimum moisture content. Both the fallow and the desiccated treatments produced moisture content values that far exceeded the optimum moisture content of the soil. Plant uptake of water by the live crop treatment from the moderately-well-drained Zoar soil produced dry conditions. The 10th percentile of the live crop treatment moisture content distribution approached the level of least compactibility for the soil. The fallow treatment, with essentially no plant uptake of water, produced the most consistent MC behavior among the treatments. Based on moisture content distributions, the fallow and the desiccated treatment plots appear more susceptible to compaction than the live crop or the residue-removed plots in Block 1.

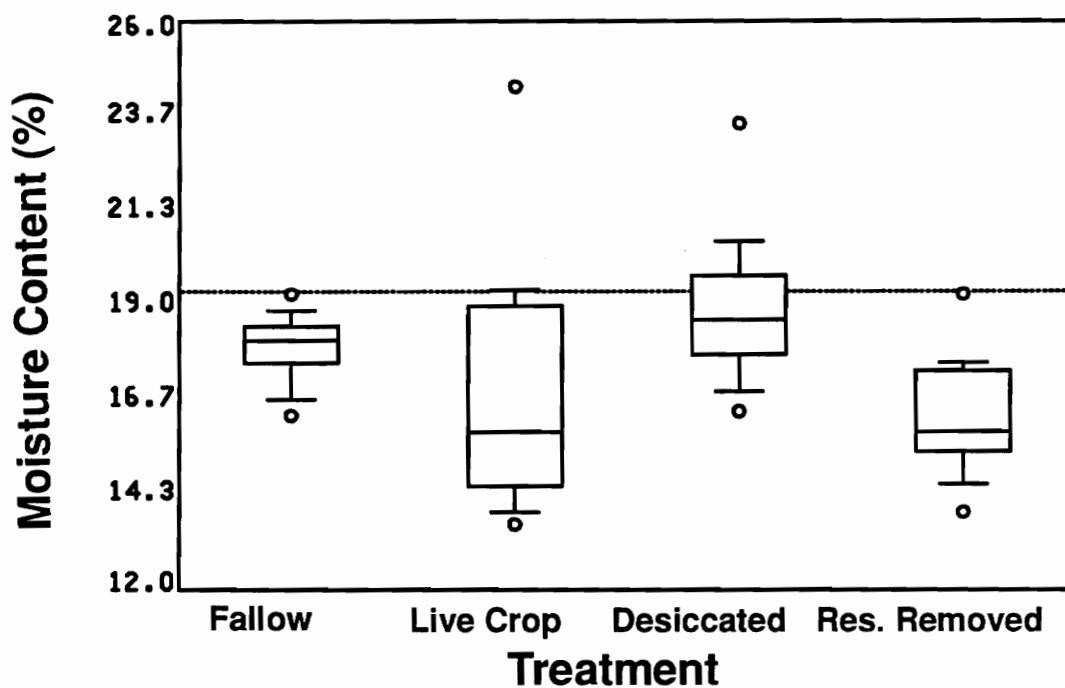


Figure 17. Moisture content box plots for the surface zone (0-10 cm) of the McGary soil (Block 2).

The median moisture content of desiccated plots was the highest among the treatments on the poorly-drained McGary soil (Figure 17). The fallow treatment produced the next highest median, but only the upper extreme values of the distribution were near the soil's optimum moisture content. The fallow treatment once again produced the most consistent MC behavior among the treatments. The live crop treatment produced the widest range of MC values, probably due to lodging that occurred in the river terrace plots. It would appear that the desiccated treatment plots were the most susceptible to compaction in

Block 2. As was the case in Block 1, the live crop and residue-removed treatments were, by virtue of lower moisture contents, less susceptible to compaction than the other treatments.

Dry Bulk Density

Bulk density was the most-easily measured of the soil parameters examined in this research. Although bulk density alone is seldom the best soil-based predictor of crop performance, it can indicate the probable states of other soil properties critical to crop growth.

Surface Zone Results. The treatments affected initial bulk density (Table 12). The residue-removed treatment mean was statistically higher than the fallow mean. A slight increase in cover-cropped treatment bulk densities was not unexpected because cover crop establishment required an additional machine pass. Even though the wheel tracks resulting from cover crop establishment were avoided during core sampling, the drill's disk openers and covering chains probably caused some degree of additional compaction across the cover-cropped plots.

Results reported in Table 12 represent treatment means pooled across the two soil blocks. Mean separation procedures based on the analysis of variance within generalized RCB experiments treat only pooled means (Hintze, 1990). Pooling, further warranted by the lack of evidence of block-treatment interaction, streamlined the presentation and interpretation of experimental results.

Table 12. Bulk density means for each treatment and for each level of traffic pooled across blocks, surface zone (g/cm³).

Treatment	Number of Passes			
	0	1	3	5
Fallow	1.232 b*	1.372	1.442 a	1.457 a
Live Crop	1.290 ab	1.356	1.401 ab	1.412 b
Desiccated	1.245 b	1.333	1.375 b	1.407 b
Residue-removed	1.313 a	1.344	1.365 b	1.396 b

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

A connection between initial bulk density and moisture content for each experimental unit was evident. Gill and VandenBerg (1967) stated that, "The data indicate that compaction caused by drying can be as great as that caused by mechanical forces." The drying of soil can cause compaction through the action of the soil water potential generating effective stresses (Dexter, 1988). In non-swelling soils, the compaction is irreversible.

For the data collected in this experiment, a negative linear relationship existed between surface zone moisture content and initial bulk density, indicated by overall correlation coefficients of -0.5746 for Pearson's r and -0.6081 for Spearman's ρ . Correlation was weakest for the residue-removed treatment data, indicating other causative agents. Unintended foot traffic resulting from harvest operations in residue-removed plots is a suspected contributor to the state of initial soil compaction associated with that treatment.

One machine pass equalized dry bulk densities across all treatments. The fallow treatment was most prone to compaction resulting from additional machine passes. No differences between any of the cover-cropped treatments existed after the first pass and all were less dense than the fallow treatment after five passes.

Why did each cover-cropped treatment outperform the fallow treatment in regard to compactness after three to five machine passes? As indicated earlier, treatment effects were confounded with moisture content effects. However, the statistical equality of surface-zone moisture content and initial bulk density between the fallow and the desiccated treatments permitted unbiased comparison of treatment performance (Table 13). By using contrasts of the treatment means at each level of traffic, it was possible to conduct an "experiment within an experiment." The approach maintained face validity by using error estimates resulting from the overall, original experiment (M. Lentner,

Professor, Department of Statistics, Virginia Tech, private communication, March 1994). The less desirable alternative was an ANOVA including only two of the original four treatments.

The linear contrast approach was also used to compare the performance of the live crop and the residue-removed treatments. The live crop and residue-removed treatments had statistically equivalent initial moisture content and bulk density means also. The analysis of the first pair of treatments permitted comparison of a cover-cropped treatment with the fallow control. The comparison of the second pair of treatments provided a gauge of the relative effects of root reinforcement and cushioning by above-ground biomass. Significance levels for the various comparisons are provided in the following table.

Table 13. Significance levels for linear contrasts of bulk density means for each level of traffic pooled across blocks, surface zone .

Comparison	Number of Passes			
	0	1	3	5
Fallow v. Desiccated	0.7048	0.3034	0.0173	0.0114
Live Crop v. Residue-removed	0.5095	0.7596	0.1769	0.4020

The linear contrast approach produced results that were in agreement with the Fisher's LSD results. The contrast significance levels provided a measure of the degree of

difference between the members of each pair of treatments. From the contrast results for the fallow versus desiccated comparison, it is clear that the two treatments moved from an initial state of essential equality to distinctly different bulk density levels after three machine passes. The difference between the two treatments widened, statistically, due to additional passes. (There was less within-treatment variance for the bulk density data after five passes than after three passes.) The other pair of treatments, however, exhibited no statistically-significant difference at any of the levels of traffic. From these comparisons, there is evidence to conclude that a combination of root reinforcement and residue cover provides a measure of protection from machine-induced soil compaction after three to five passes. Furthermore, the protection appears to result, in large part, from root reinforcement.

Distinctions between the treatments were also evident in the changes in bulk density that took place following each machine pass. Cumulative changes in dry bulk density for the treatments are presented in Table 14. Bulk density difference data were developed by subtracting the overall uncompacted mean bulk density for a plot from individual wheel track sample values. The trends in cumulative bulk density differences provide a measure of the resilience of the cover-cropped treatments after multiple machine passes.

Table 14. Bulk density difference means for each treatment and for each level of traffic pooled across blocks, surface zone (g/cm³).

Treatment	Number of Passes		
	1	3	5
Fallow	0.140 a*	0.209 a	0.225 a
Live Crop	0.066 b	0.111 b	0.121 bc
Desiccated	0.088 ab	0.129 b	0.162 b
Residue-removed	0.031 b	0.051 c	0.083 c

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$.

The bulk density difference caused by traffic was greater for the fallow treatment than for any of the cover-cropped treatments after three and five passes. The residue-removed treatment exhibited the least cumulative change in bulk density after three machine passes, but suffered a relatively large increase in BD due to additional traffic. The superior performance of the residue-removed treatment compared to the fallow treatment probably resulted from its lower moisture content and higher initial bulk density. There was no significant difference between the live crop and residue-removed treatments after five passes. The traffic-induced changes in bulk density for the live crop and the desiccated treatments were not significantly different at any level of traffic. The live crop treatment failed to produce an advantage over the desiccated treatment despite its lower soil moisture contents and higher crop yields.

The following figures were produced to illustrate the behavior of each treatment at different levels of machine traffic. Bulk density difference means were plotted versus the number of machine passes. Plots were prepared for each treatment in each block. Based on the patterns produced by the plotted data, curves were fitted and parameter values for the appropriate models defined. Two basic models were shown to fit most of the data quite well. One was of the form $Y = aX^b$. Canarache et al. (1984) used the model to describe changes in soil physical properties due to repeated machine traffic. The other, known as the monomolecular model, is one of a number of growth curves used to describe physical processes (Hintze, 1992b). The model was of the form $Y = a(1 - e^{-b(X-c)})$. The value of a can take on physical significance in certain situations. In this analysis of soil compaction, a represented an estimate of the maximum change in bulk density that a treatment would incur. The magnitude of b gauged the rate at which Y approached the asymptotic value a . The value of c was set to zero to ensure that each curve would include the origin. The equation describing each fitted curve is provided along with goodness of fit and model significance statistics in Figures 18 - 25.

Note: Characteristics of the plotting routine used to produce the figures for bulk density, and later for capillary porosity and noncapillary porosity, resulted in the slight lack of correspondence between the locations of horizontal axis labels and plotted data points. Thus, interpolation of data from the figures should not be attempted, and the equations should be used instead.

Equation: $Y = 0.248(1 - e^{-1.407X})$

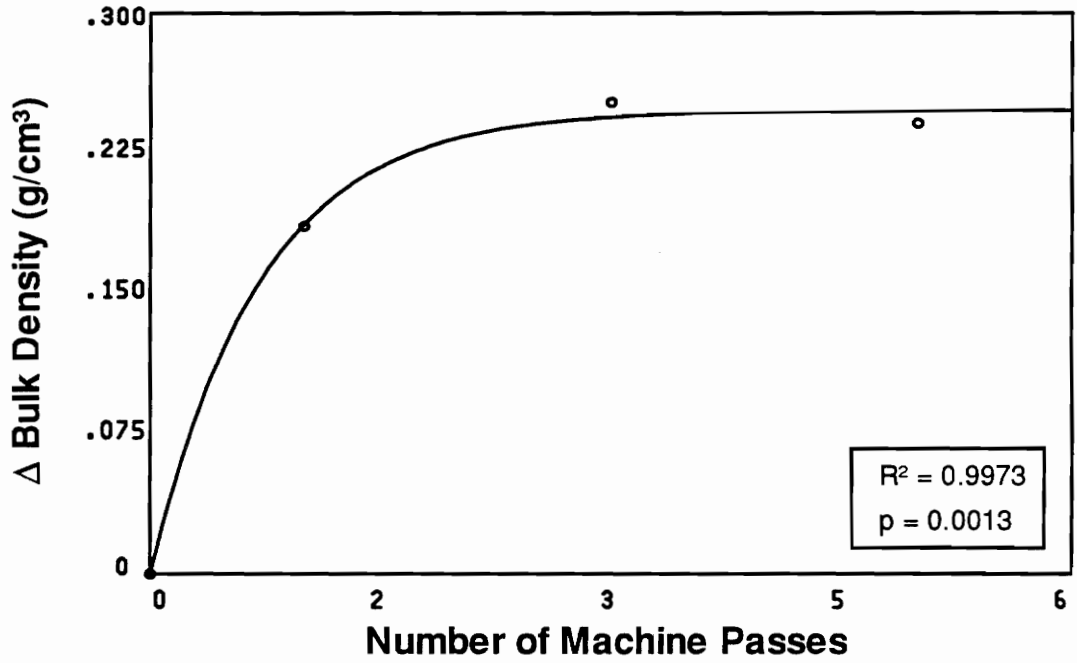


Figure 18. Fallow treatment bulk density response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 0.096X^{0.485}$

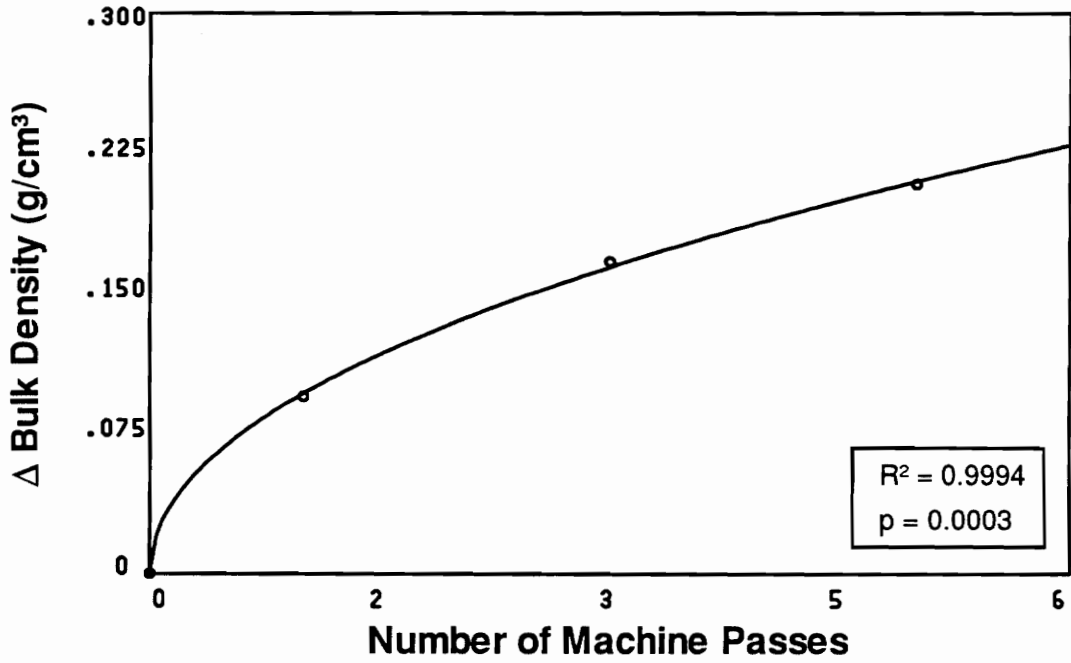


Figure 19. Fallow treatment bulk density response to machine traffic on the McGary soil (Block 2).

Equation: $Y = 0.102(1 - e^{-1.310X})$

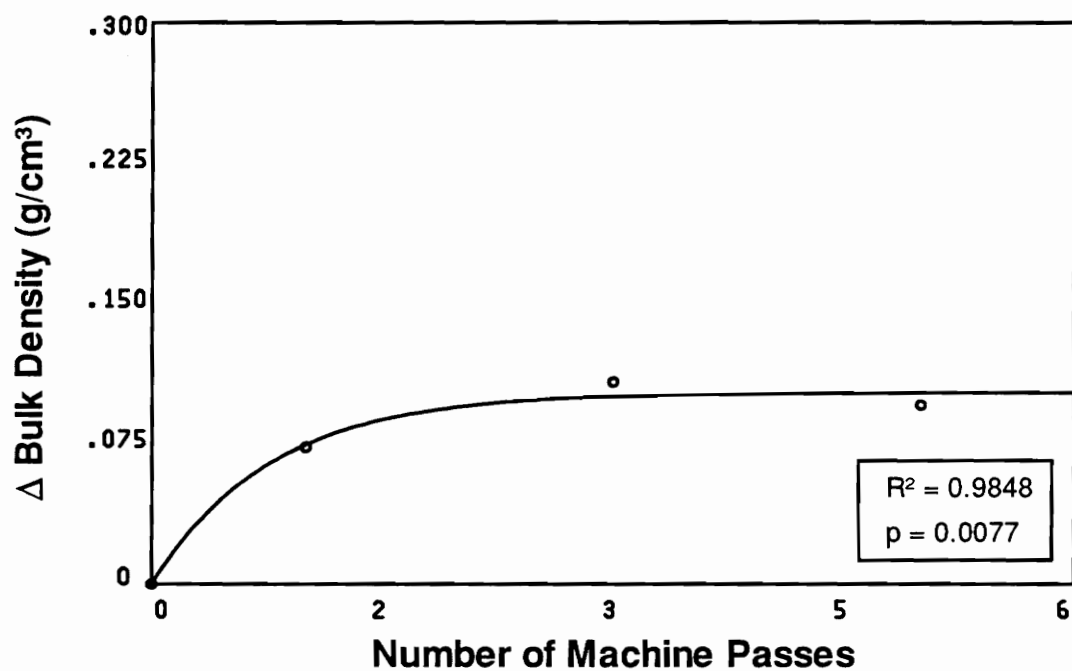


Figure 20. Live crop treatment bulk density response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 0.169(1 - e^{-0.395X})$

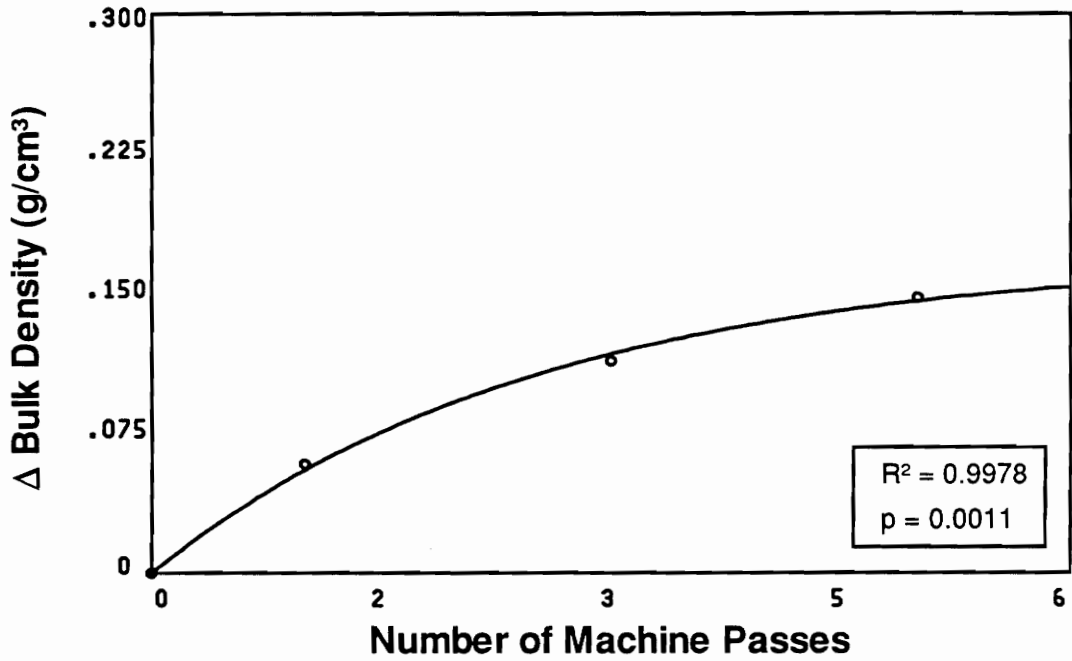


Figure 21. Live crop treatment bulk density response to machine traffic on the McGary soil (Block 2).

Equation: $Y = 0.116X^{0.229}$

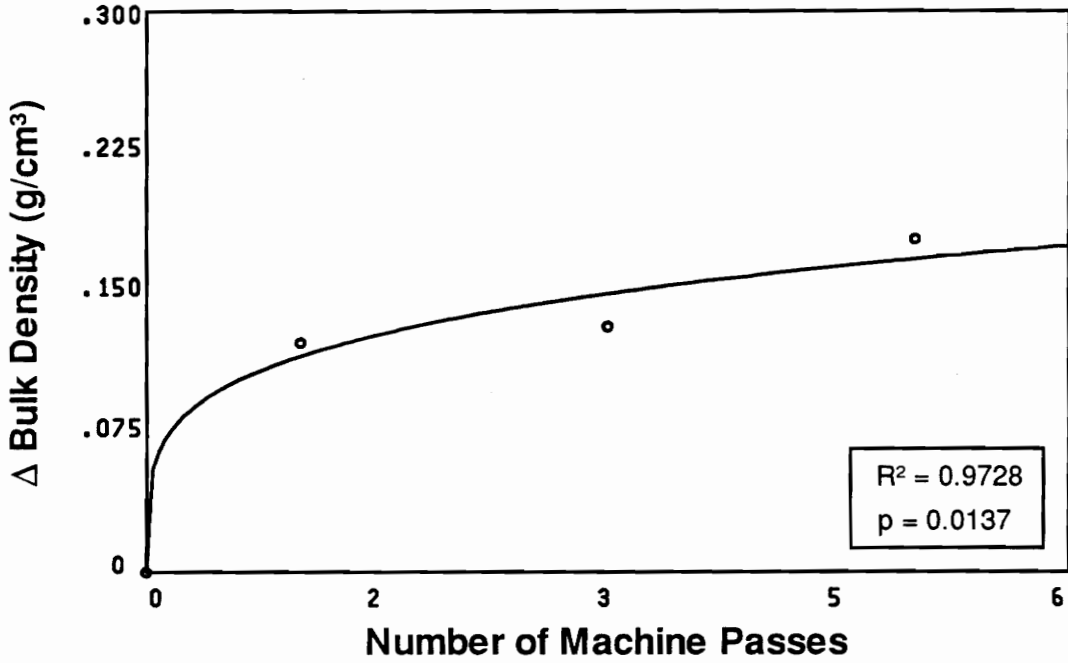


Figure 22. Desiccated treatment bulk density response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 0.170(1 - e^{-0.416X})$

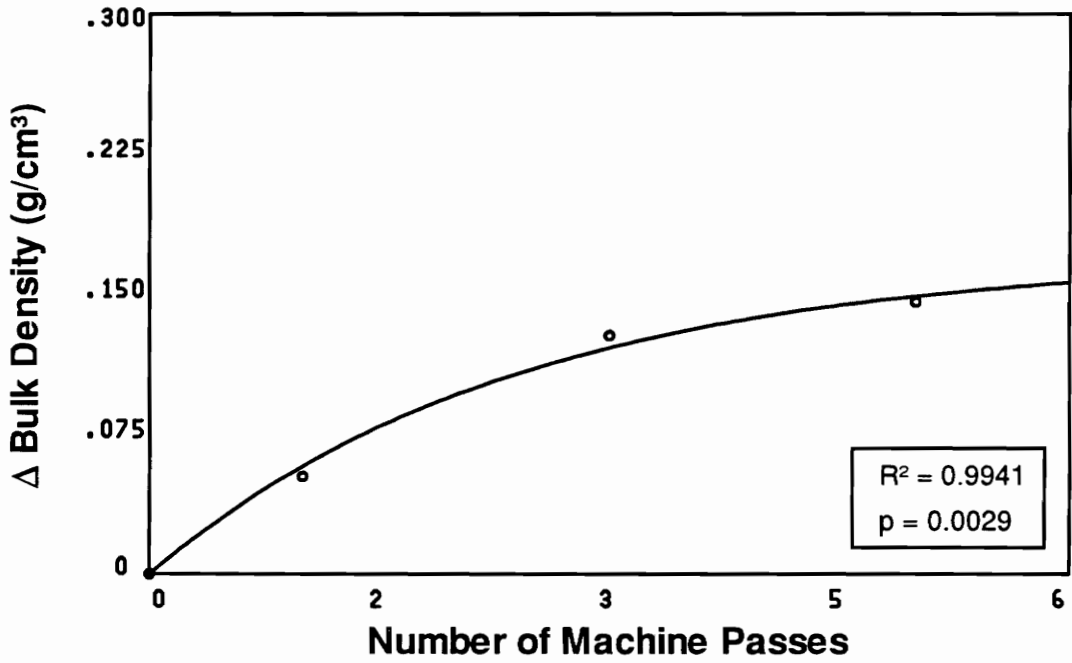


Figure 23. Desiccated treatment bulk density response to machine traffic on the McGary soil (Block 2).

Equation: $Y = 0.039X^{0.475}$

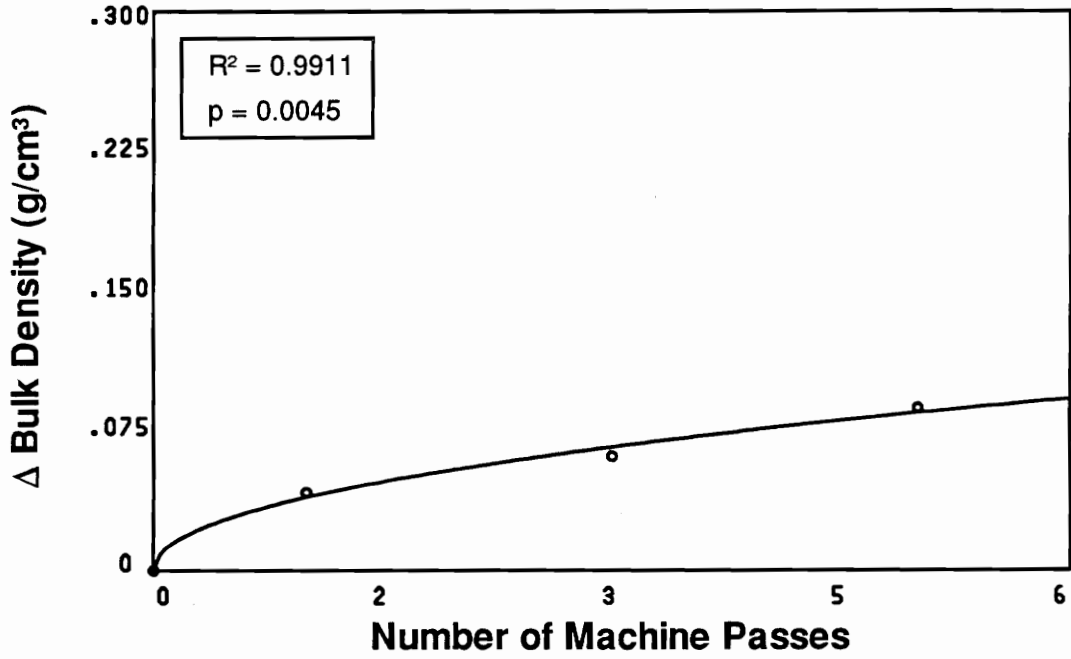


Figure 24. Residue-removed treatment bulk density response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 0.015X^{0.992}$

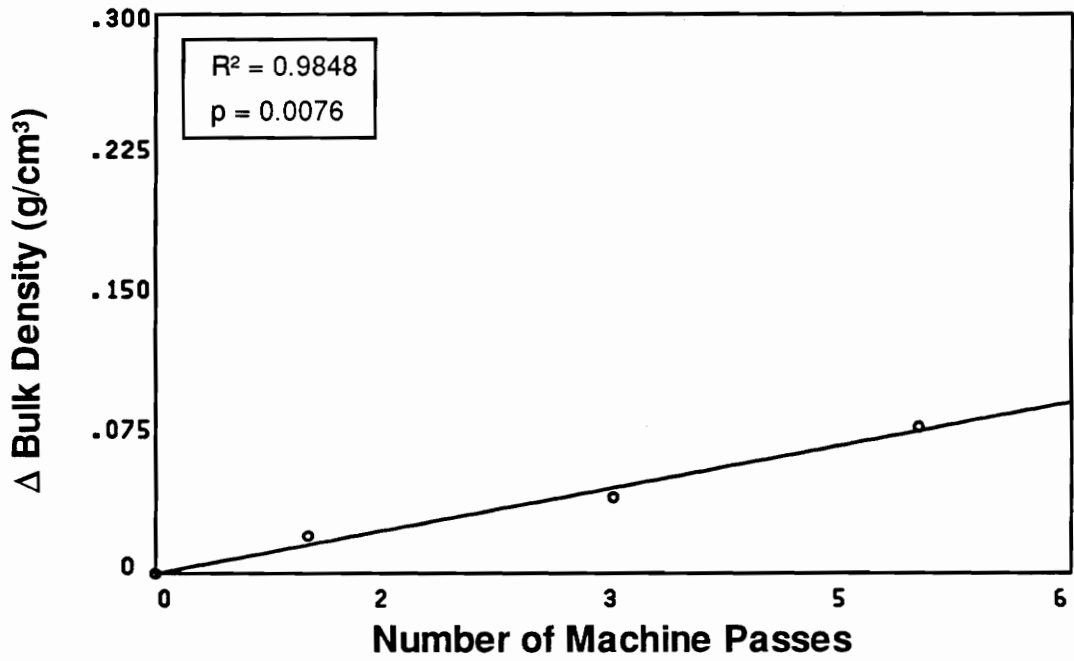


Figure 25. Residue-removed treatment bulk density response to machine traffic on the McGary soil (Block 2).

All of the fitted curves produced high R^2 values and each model was statistically significant. Both measures, R^2 and p , are subject to interpretation and neither is without controversy, however (Hintze, 1992b). In particular, R^2 is highly sensitive to the number of observations. The smaller the sample size, the larger the value of R^2 . The statistics were presented to provide a quantitative complement to the visual assessment of goodness of fit. In addition, statements made concerning treatment and/or soil performance are based on quantitative comparisons rather than statistical comparisons unless otherwise noted.

The fallow treatment responses to machine traffic were described well by the fitted curves shown in Figures 18 and 19. The experimental units clearly reached a bulk density change plateau within five machine passes in Block 1. The change in bulk density was more gradual in Block 2, with the fitted curve indicating the potential for further compaction at higher levels of traffic on the McGary soil. The difference in soil response to machine traffic between the two blocks was due in part to soil textural differences. The McGary soil, with its higher surface-zone clay content, responded more slowly to repeated wheel loading. The soil in the Block 2 fallow treatment exhibited behavior similar to that reported by Burger et al. (1985). The bulk density response was proportional to the number of passes raised to the exponent $b = 0.485$.

The initial relative compaction (the ratio of initial bulk density to the maximum Proctor bulk density for a soil) was essentially identical between blocks for each treatment. The difference in the magnitude of bulk density change between blocks could have resulted in part from the difference in moisture content states for the fallow treatment. In Block 1, the central tendency of the fallow treatment's moisture content distribution was closer to the soil's optimum moisture content than it was in Block 2.

The live crop treatment in Block 1 reached an apparent bulk density plateau following three machine passes (Figure 20). In Block 2, soil bulk density increased due to additional traffic between the three- and five-pass traffic levels (Figure 21). The presence of the live crop affected the magnitude of soil bulk density response compared to the fallow treatment, but the manner in which each soil responded to multiple machine passes was not greatly affected.

The equation describing the response of the desiccated treatment in Block 2 was quite similar to that of the live crop treatment (Figure 23). In Block 1, the treatment mean reached an apparent plateau within three machine passes (Figure 22). However, the protection against bulk density change afforded by the desiccated treatment appeared to break down by the fifth machine pass. Still, the change in bulk density resulting from three or more machine passes was clearly less than that of the fallow treatment in both blocks.

The continuous upward trend in cumulative bulk density change experienced by the residue-removed treatment was better described by the $Y = aX^b$ model than by the monomolecular model (Figures 24 and 25). Even though the magnitude of bulk density change was much smaller than that of the fallow treatment, there was no evidence to indicate at what traffic level the residue-removed treatment bulk density would plateau. The soil in the Block 1 residue-removed treatment exhibited behavior similar to that of the fallow treatment in Block 2. In Block 1, soil response was proportional to an approximation of the square root of the number of machine passes ($b = 0.475$). In Block 2, the response approximated a straight line ($b = 0.992$), quite different from the other treatments.

Subsurface Zone Results. Initial bulk density means were greater in the subsurface zone than in the surface soil zone for all treatments (Table 15). After five passes, only the desiccated treatment had a surface-zone bulk density mean that was lower than the subsurface bulk density mean ($p = 0.0886$). Machine traffic had compacted the surface zones of the other treatments to bulk density levels that were equivalent to those of the subsurface zone. Significant compaction effects, as evidenced by machine-induced changes in soil bulk density, did not extend to the subsurface zone, however. There were no statistically-significant differences among the treatment means at any level of traffic.

Table 15. Bulk density means for each treatment and for each level of traffic pooled across blocks, subsurface zone (g/cm³).

Treatment	Number of Passes			
	0	1	3	5
Fallow	1.445*	1.442	1.485	1.457
Live Crop	1.444	1.415	1.443	1.439
Desiccated	1.414	1.433	1.417	1.453
Residue-removed	1.448	1.415	1.458	1.432

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

Even though the fallow treatment bulk density mean exhibited variation from one traffic level to another, there was a consistent lack of difference due to traffic in the subsurface soil for all treatments. Numerical inconsistencies in the data could have resulted from variations in tillage disturbance patterns, surface profile boundary effects at locations where the profile was shallow, or from sampler-induced variation. Collection and extraction of samples were more difficult for the subsurface zone than for the surface zone. The point at which the sampler filled with soil was more difficult to ascertain during subsurface core sampling. Extraction of the sampler body from the subsurface soil occasionally required hammering.

A series of *two-sample t-tests* were performed to compare zero-pass and five-pass bulk density data. The tests revealed no significant differences within the subsurface zone for any of the treatments.

Physical Significance. Statistical significance does not necessarily translate into physical or practical significance. No pooled treatment means reached bulk density levels that would cause physical impedance of crop root growth. However, two of the fallow treatment experimental units in the Zoar soil block reached growth-limiting bulk densities as defined by Daddow and Warrington (1983). By using the GLBD Textural Triangle (Figure 1), a growth-limiting bulk density was determined for each soil type. One of the fallow treatment replicates exceeded the GLBD threshold for the Zoar soil, 1.5 g/cm^3 , after one machine pass. Another fallow replicate exceeded the bulk density threshold after three passes. No other treatment replicate in either block was at a growth-limiting density level, even after five machine passes.

If one examines the magnitude of the bulk density difference between any cover-cropped treatment mean and the fallow treatment mean after five machine passes, the number appears quite small ($0.05 - 0.06 \text{ g/cm}^3$). However, it is only necessary to recall the results of the Standard Proctor test to put such numbers into the proper perspective. The difference between the bulk density value achieved at the optimum moisture content and the value for the soil at its least compactible moisture level was 0.10 g/cm^3 for the Zoar

soil and 0.13 g/cm^3 for the McGary soil. It is also necessary to realize that while compaction at a depth of 7.5 cm or less could be ameliorated by tillage in a conventional cropping system, systems that do not involve regular tillage can be adversely affected by excessive compaction at or near the soil surface.

A second set of core samples was collected from two replicates of each treatment in Block 1 on October 15 and 16. The second round of sampling was timed to roughly coincide with corn harvest. There was interest in assessing season-long weathering effects on compacted soil condition. Sampling was limited to the plots on the Zoar soil due to the disruption of the river terrace site by errant machine traffic. The samples, taken from the surface zone, were collected and analyzed to gauge the persistence of compaction effects in the tractor wheel tracks. Two-sample t-tests were performed to compare dry bulk density values collected in early June with those collected in mid-October. All treatments showed a reduction in bulk density in the one-pass wheel tracks. The reduction in the fallow treatment replicates was statistically significant. There was no evidence of significant change in bulk density in either the three-pass or five-pass wheel tracks for any treatment.

Analysis of the end-of-season data revealed significant differences among the treatment means for the five-pass traffic level. Fisher's LSD test showed that the fallow treatment mean was significantly different (higher) than any of the cover-cropped bulk density

means. Compaction effects persisted through the growing season in the multi-pass wheel tracks.

Pore Size Distribution

Total soil porosity, calculated directly from bulk density, provides a mirror image of bulk density performance. Conditions that increase bulk density decrease total soil porosity. Rather than simply restating the bulk density results, pore size distribution data were analyzed to provide insight into machine-induced effects on soil air- and water-holding and transmission characteristics. Capillary porosity was measured by the change in weight of a soil core as it was dried from its equilibrium weight, achieved on the tension table, to its oven-dry weight. Noncapillary porosity represented the difference between the total volume of voids and the capillary pore volume within the boundaries of a soil core.

Capillary Porosity - Surface Zone Results. Initial capillary porosity means were affected by the treatments (Table 16). The live crop and the residue-removed treatment means were significantly higher than the fallow and the desiccated treatment means. The same pairing of treatments seen in initial bulk density conditions - fallow and desiccated, live crop and residue removed - was evident in the capillary porosity data. The pair of treatments with the higher bulk density means had the higher capillary porosity means.

Table 16. Capillary porosity means for each treatment and for each level of traffic pooled across blocks, surface zone (%).

Treatment	Number of Passes			
	0	1	3	5
Fallow	29.15 b*	33.27	33.96	34.67
Live Crop	31.97 a	32.59	34.38	34.41
Desiccated	30.07 b	32.57	34.25	34.66
Residue-removed	31.61 a	32.83	32.84	33.47

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

As was the case with bulk density, one machine pass equalized capillary porosity means across all treatments. However, the one-pass live crop treatment mean was not significantly different from the zero-pass mean ($p = 0.4972$). Soil capillary porosity levels for all treatments increased due to three machine passes, but no pooled treatment mean increased significantly between the three- and five-pass traffic levels. The treatment means remained statistically equivalent through three and five machine passes. Analysis of variance revealed no significant block-treatment interaction at any level of traffic.

Linear contrasts were used to compare the performance of the two chosen sets of treatments (Table 17).

Table 17. Significance levels for linear contrasts of capillary porosity means for each level of traffic pooled across blocks, surface zone .

Comparison	Number of Passes			
	0	1	3	5
Fallow v. Desiccated	0.2552	0.3529	0.7355	0.9944
Live Crop v. Residue-removed	0.6493	0.7538	0.0855	0.2523

There was no statistically-significant difference between the measured capillary porosities of the fallow and the desiccated treatments at any level of traffic. The comparison between the live crop and the residue-removed treatments produced a nominally-significant result at the three-pass traffic level. An "unprotected" Fisher's LSD test would have produced the same result. However, the same rationale that prevents the use of Fisher's test if ANOVA produces a non-significant result was applied here. Without corroborating evidence of difference from the overall analysis of variance, the indication of significance was disregarded. There was no other evidence of differences between the two treatments at the other levels of traffic. A summary of the changes in capillary porosity that took place within each set of treatment replicates is presented in Table 18.

Table 18. Capillary porosity difference means for each treatment and for each level of traffic pooled across blocks, surface zone (%).

Treatment	Number of Passes		
	1	3	5
Fallow	4.12 a*	4.81 a	5.52 a
Live Crop	0.62 c	2.40 b	2.43 b
Desiccated	2.51 b	4.18 a	4.59 a
Residue-removed	1.22 bc	1.23 b	1.86 b

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$.

There were significant differences in treatment response to machine traffic above and beyond the distinction between the two treatment pairs. In particular, the very small initial response by the live crop treatment merited notice. Rather than representing outstanding performance, the result represented an initial capillary porosity mean that was unusually large. This result stemmed from the presence of a small number of soil cores taken from an untracked area of Block 1 that produced exceptionally high bulk density and capillary porosity measurements. The situation was revealed when treatment responses were plotted for each block. The following figures were produced to illustrate the behavior of each treatment at different levels of machine traffic. Capillary porosity response curves and an equation describing each fitted curve, along with goodness-of-fit and model significance statistics, are provided in Figures 26-27 and 29-33. No curve was fitted to the capillary porosity change data for the live crop treatment in Block 1 (Figure 28).

Equation: $Y = 4.496X^{0.139}$

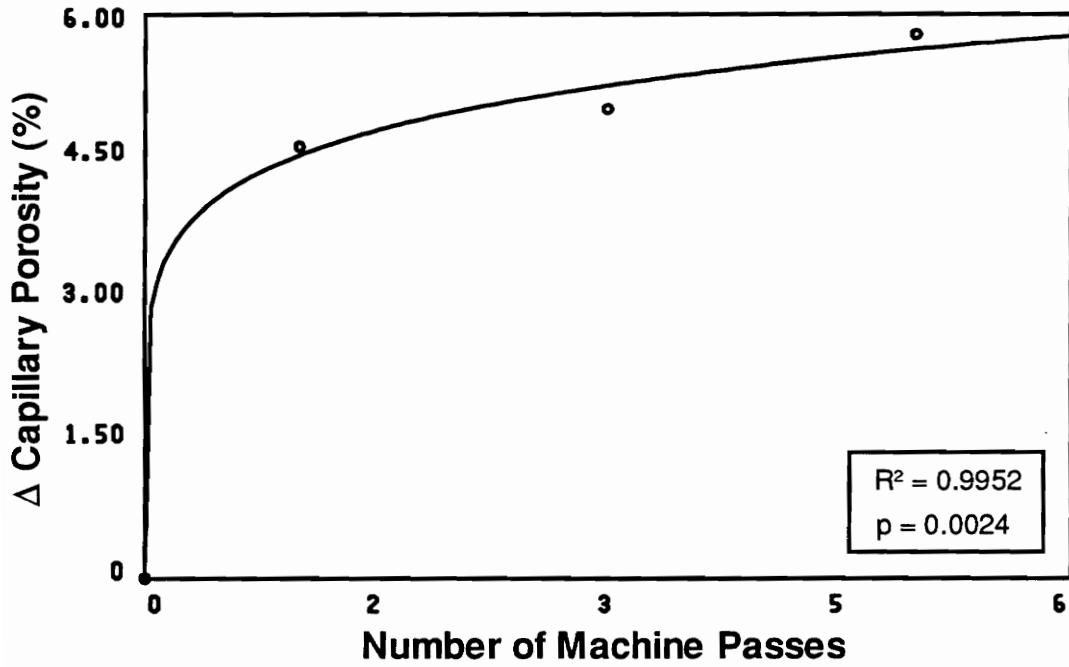


Figure 26. Fallow treatment capillary porosity response to machine traffic on the Zoar soil (Block 1).

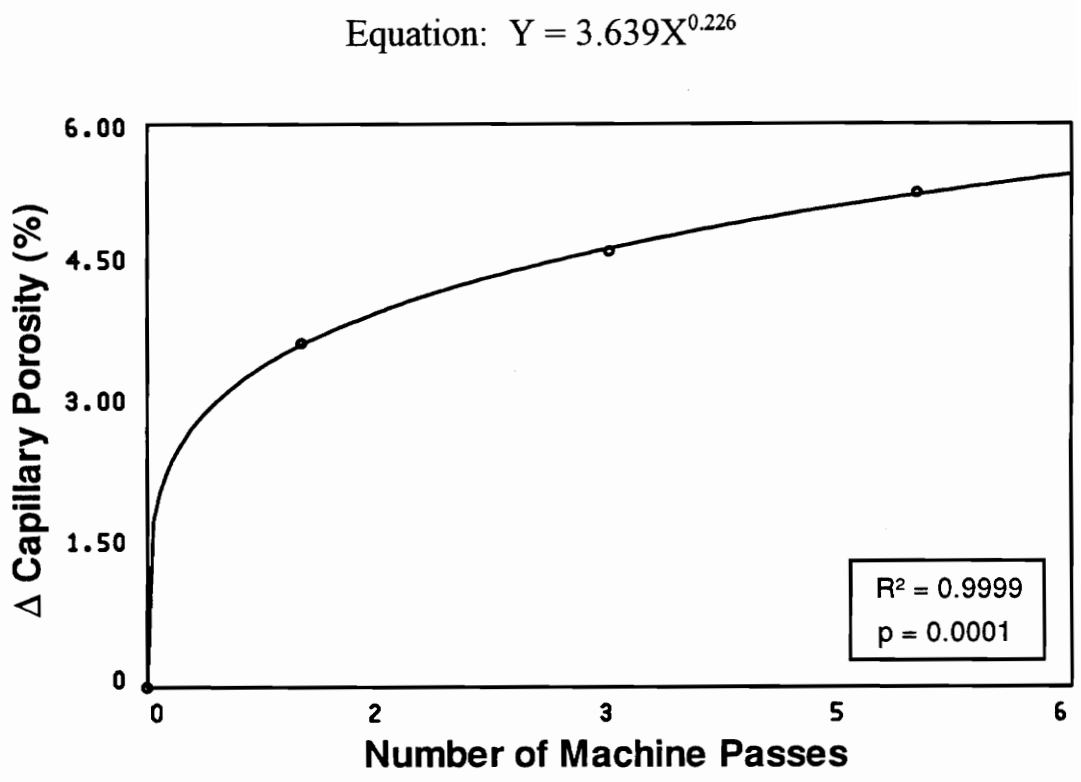


Figure 27. Fallow treatment capillary porosity response to machine traffic on the McGary soil (Block 2).

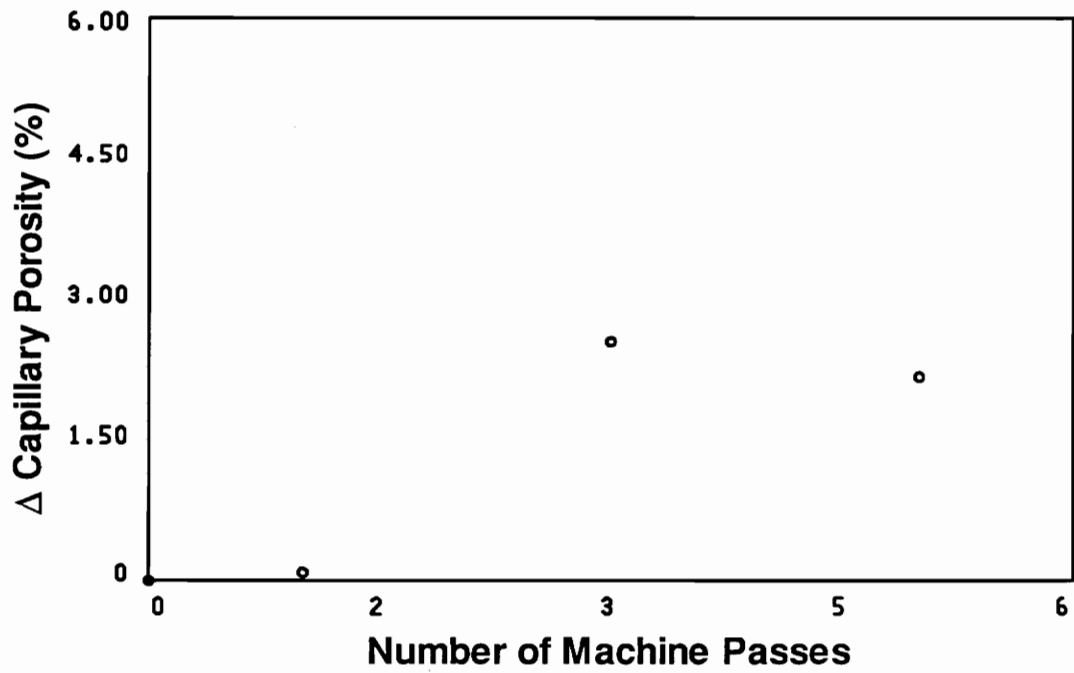


Figure 28. Live crop treatment capillary porosity response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 2.944(1 - e^{-0.493X})$

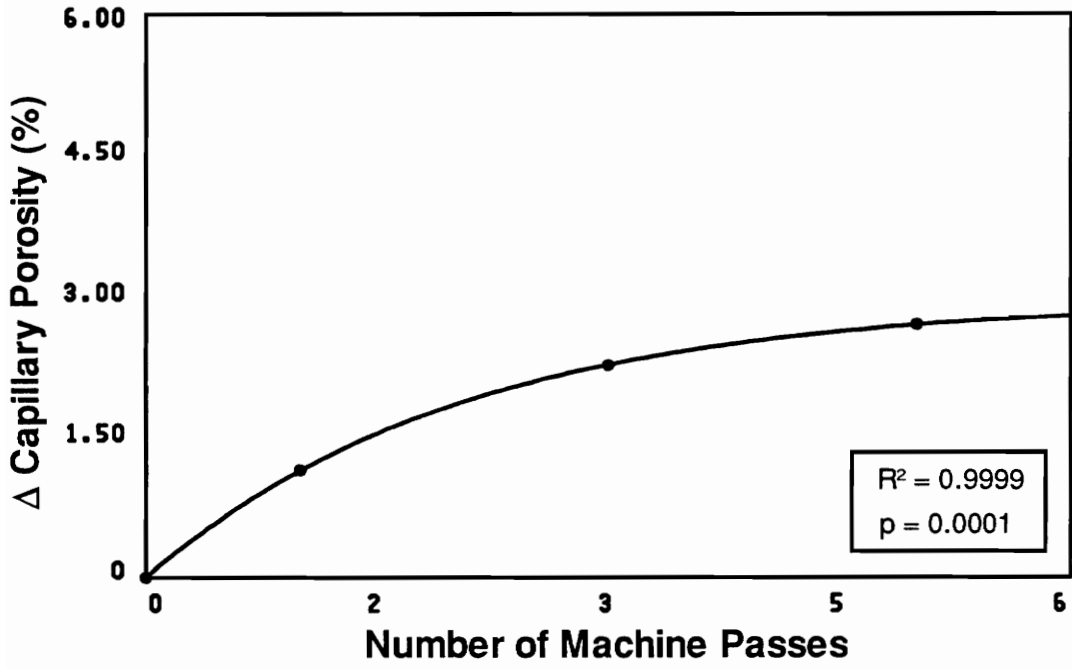


Figure 29. Live crop treatment capillary porosity response to machine traffic on the McGary soil (Block 2).

Equation: $Y = 5.735(1 - e^{-0.627X})$

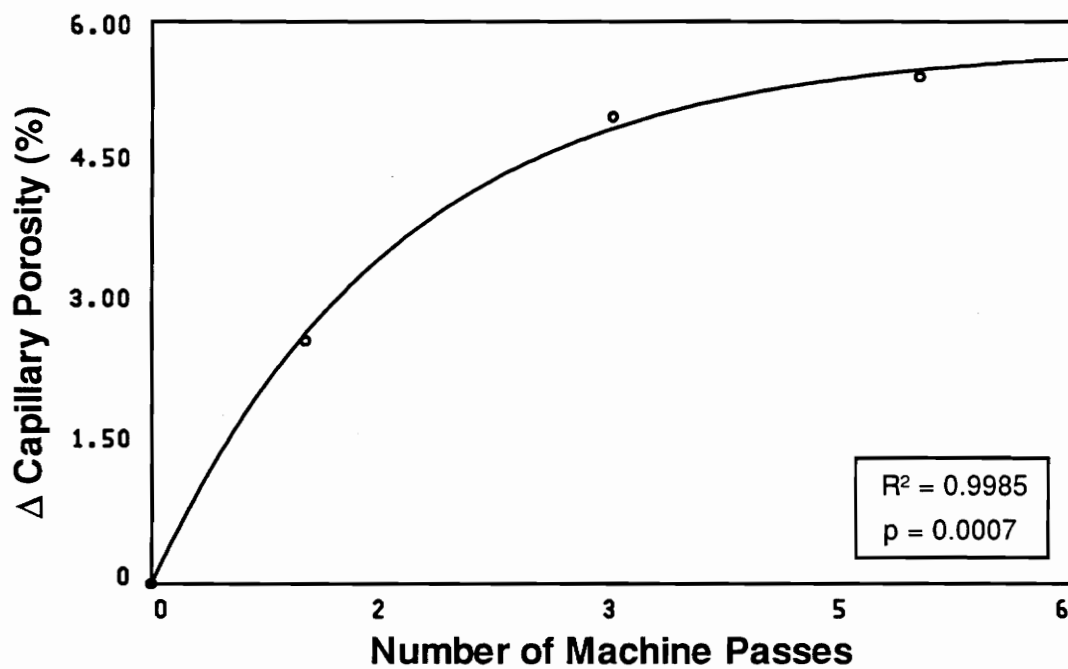


Figure 30. Desiccated treatment capillary porosity response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 2.449X^{0.276}$

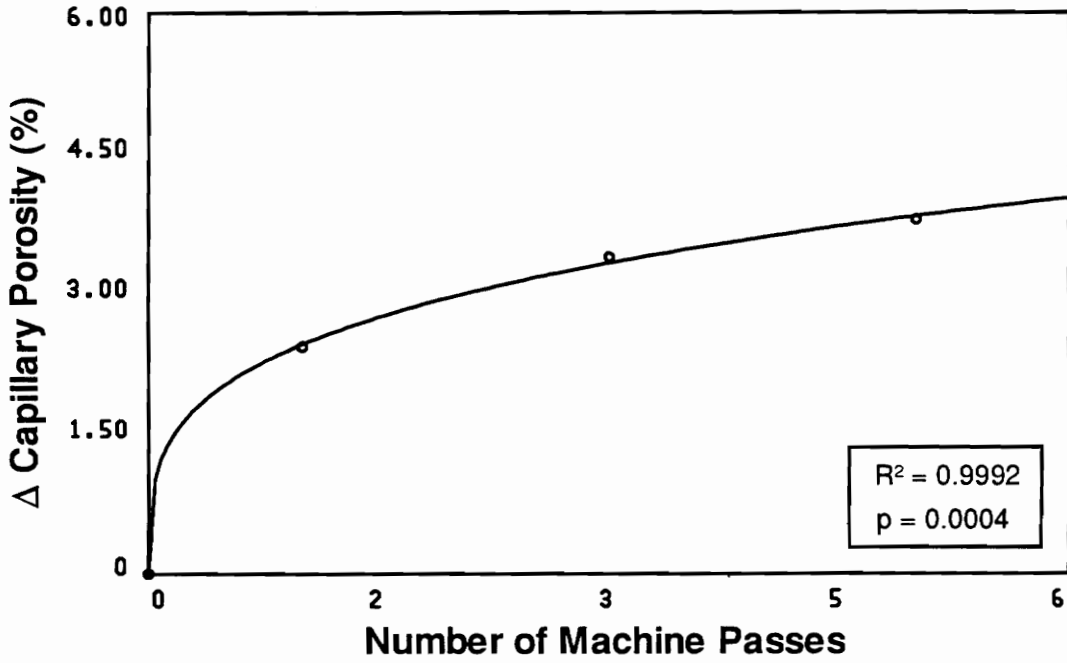


Figure 31. Desiccated treatment capillary porosity response to machine traffic on the McGary soil (Block 2).

Equation: $Y = 1.951X^{0.201}$

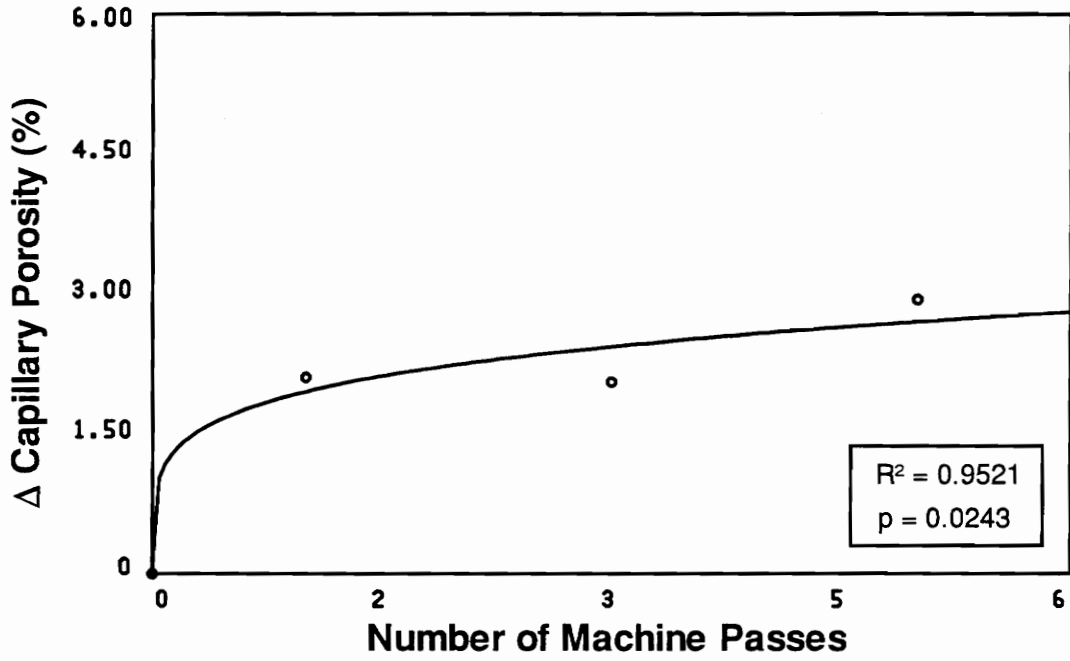


Figure 32. Residue-removed treatment capillary porosity response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = 0.258X^{0.647}$

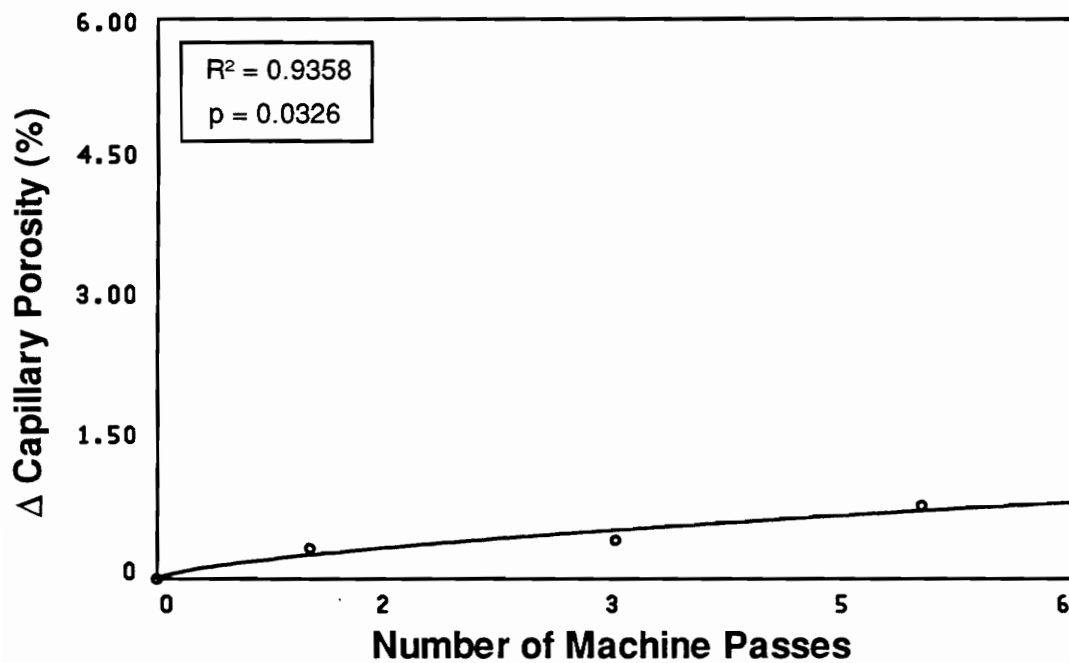


Figure 33. Residue-removed treatment capillary porosity response to machine traffic on the McGary soil (Block 2).

With the exception of the live crop treatment in Block 1, all of the fitted curves produced high R^2 values and each model was statistically significant. The fallow treatment response to machine traffic in Block 1 was better described by the $Y = aX^b$ model than by a growth curve such as that used for the Block 1 fallow treatment bulk density response (Figures 18 and 26). In Block 1, the growth in bulk density had clearly reached a plateau by the three-pass traffic level. Capillary porosity was increasing even at the five-pass level. The fallow treatment in Block 2 responded with steady increases in capillary porosity through five machine passes, as well (Figure 27).

The erratic behavior of the capillary porosity change data for the live crop treatment in Block 1 (Figure 28) resulted from the high capillary porosity of cores taken from areas in one experimental unit that were supposed to be untracked. It should be noted, however, that the three- and five-pass porosity differences in Block 1 were comparable in magnitude to those in Block 2 (Figure 29), in spite of the high initial capillary porosity and the relatively low moisture content of the Zoar soil.

Capillary porosities for soil core samples taken from the desiccated treatment sites were shown to be increasing in both blocks between the three- and five-pass traffic levels (Figures 30 and 31). The responses to one traffic pass were essentially identical between the blocks. In Block 1, the initial response was followed by a large increase in capillary porosity at the three-pass traffic level. The magnitude of porosity change for the

desiccated treatment in Block 1 was similar to that of the fallow treatment at the three- and five-pass traffic levels. The rate of increase was smaller for the cover-cropped treatment at the highest traffic level, however. In Block 2, the difference between the fallow and the desiccated treatment responses to multiple machine passes was conspicuous.

The residue-removed treatment suffered relatively small increases in capillary porosity (Figures 32 and 33). Blocks 1 and 2 performed similarly in that there was little difference, within each block, between capillary porosities at the one-pass and the three-pass traffic levels. Both blocks experienced increases due to additional machine passes, however.

Capillary Porosity - Subsurface Zone Results. Initial capillary porosity means were greater in the subsurface zone than in the surface soil zone for the fallow treatment ($p = 0.0001$) and for the desiccated treatment ($p = 0.0201$) (Table 19). It took only one machine pass to increase the fallow treatment surface-zone capillary porosity mean to a level greater than in the subsurface zone ($p = 0.0533$). After three machine passes, the surface-zone means exceeded those of the subsurface zone for the fallow ($p = 0.0114$) and the desiccated ($p = 0.0102$) treatments. After five passes, only the live crop surface-zone mean had not been driven to a higher level than the subsurface-zone mean. Significant machine-induced changes in capillary porosity did not extend to the subsurface zone, however.

Table 19. Capillary porosity means for each treatment and for each level of traffic pooled across blocks, subsurface zone (%).

Treatment	Number of Passes			
	0	1	3	5
Fallow	31.54 b*	31.47	31.52 b	31.53 b
Live Crop	32.99 a	32.85	33.52 a	33.20 a
Desiccated	31.62 b	31.82	31.75 b	32.26 ab
Residue-removed	32.60 a	32.49	32.07 b	31.41 b

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

Capillary porosity was more sensitive to pre-test treatment effects than was bulk density. There were significant differences among the treatments initially. Capillary porosity means for the live crop and the residue-removed treatments were higher than those of the fallow and the desiccated treatments. The initial capillary porosity means reflected subsurface-zone moisture content levels (Table 10). The subsurface soil that suffered drying-induced compaction produced a higher level of capillary porosity.

There was very little variation within the treatments from one traffic level to another. A series of two-sample t-tests were performed, one for each treatment in each block, to compare zero-pass capillary porosity data to that of the one-pass, the three-pass and the five-pass traffic levels. The tests revealed no significant differences from initial conditions

within the subsurface zone for any of the treatments at any level of traffic. There was, therefore, no evidence of significant treatment effects on subsurface-soil response to machine traffic.

Effects on Capillary Porosity - Physical Significance. The lack of any clearly-defined growth-limiting capillary porosity thresholds precludes a discussion of the practical significance of experimental results based on such a standard. Nonetheless, it must be remembered that machine-induced changes in soil pore size distribution can significantly affect plant growth conditions related to air and water movement within the soil matrix. When compaction increases capillary porosity at the expense of macroporosity, soil behavior can change markedly.

Noncapillary Porosity - Surface Zone Results. The treatments affected initial noncapillary porosity means. Desiccated and fallow treatment means were greater than those of the live crop and residue-removed treatments. The differences among initial noncapillary porosity means corresponded directly to the differences among surface-zone moisture content means (Table 9). Once again, one machine pass led to statistical equality among all treatment means. However, soil particle rearrangement resulting from further traffic caused reductions in noncapillary porosity and significant differences between cover-cropped and fallow treatment means (Table 20).

Table 20. Noncapillary porosity means for each treatment and for each level of traffic pooled across blocks, surface zone (%).

Treatment	Number of Passes			
	0	1	3	5
Fallow	24.36 a*	14.95	11.64 b	10.36 b
Live Crop	19.34 b	16.24	12.75 b	12.33 a
Desiccated	22.94 a	17.13	13.88 ab	12.25 a
Residue-removed	18.83 b	16.45	15.67 a	13.85 a

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

The overall noncapillary porosity mean for the fallow treatment was driven to the ten percent threshold by five machine passes. All cover-cropped treatment means were

significantly higher than that of the fallow treatment after five passes. Final cover-cropped treatment means were 18 to 34 percent higher than the fallow treatment mean.

The pairing of treatments for the purpose of constructing linear contrasts of means was still appropriate for the analysis of noncapillary porosity data. Initial noncapillary porosity means for the treatment pairs - fallow and desiccated, live crop and residue-removed - were not significantly different (Table 21).

Table 21. Significance levels for linear contrasts of noncapillary porosity means for each level of traffic pooled across blocks, surface zone .

Comparison	Number of Passes			
	0	1	3	5
Fallow v. Desiccated	0.4454	0.2256	0.1456	0.0747
Live Crop v. Residue-removed	0.7846	0.9079	0.0619	0.1459

Noncapillary pores are more susceptible than capillary pores to alteration by machine traffic. For noncapillary porosity, there were significant differences, based on both ANOVA and linear contrast results, between members of the treatment pairs. After five machine passes, the desiccated treatment mean was significantly higher than the fallow mean. The residue-removed treatment had a significantly-higher noncapillary porosity mean than the live crop treatment after three machine passes. After five passes, the

difference was no longer statistically significant due to a rather large drop in the residue-removed treatment mean between the three- and five-pass traffic levels. Traffic-induced changes in noncapillary porosity for all treatments are summarized in Table 22.

Table 22. Noncapillary porosity difference means for each treatment and for each level of traffic pooled across blocks, surface zone (%).

Treatment	Number of Passes		
	1	3	5
Fallow	-9.41 b*	-12.71 c	-13.99 c
Live Crop	-3.10 a	-6.59 b	-7.01 ab
Desiccated	-5.81 a	-9.06 b	-10.69 bc
Residue-removed	-2.39 a	-3.17 a	-4.98 a

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$.

The fallow treatment suffered the greatest reductions in noncapillary porosity at all traffic levels. The residue-removed treatment produced the best performance among all treatments. The changes in noncapillary porosity for the live crop and the desiccated treatments were not statistically different at any level of traffic. Noncapillary porosity response curves are presented in Figures 34 - 41.

Equation: $Y = -14.769(1 - e^{-1.534X})$

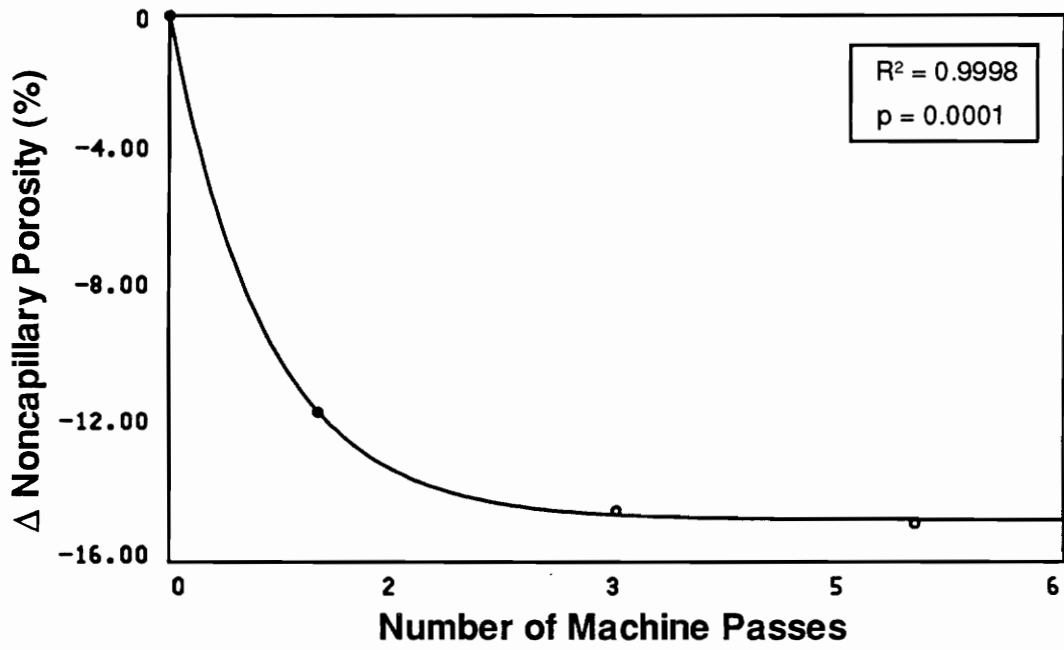


Figure 34. Fallow treatment noncapillary porosity response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = -7.243X^{0.370}$

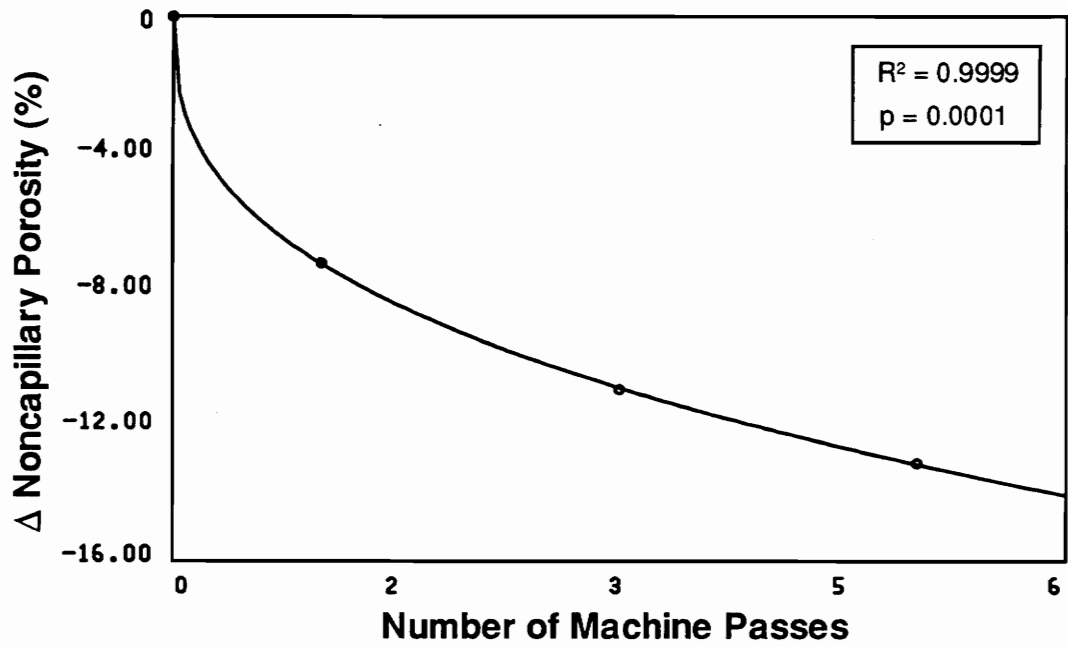


Figure 35. Fallow treatment noncapillary porosity response to machine traffic on the McGary soil (Block 2).

Equation: $Y = -6.502(1 - e^{-0.715X})$

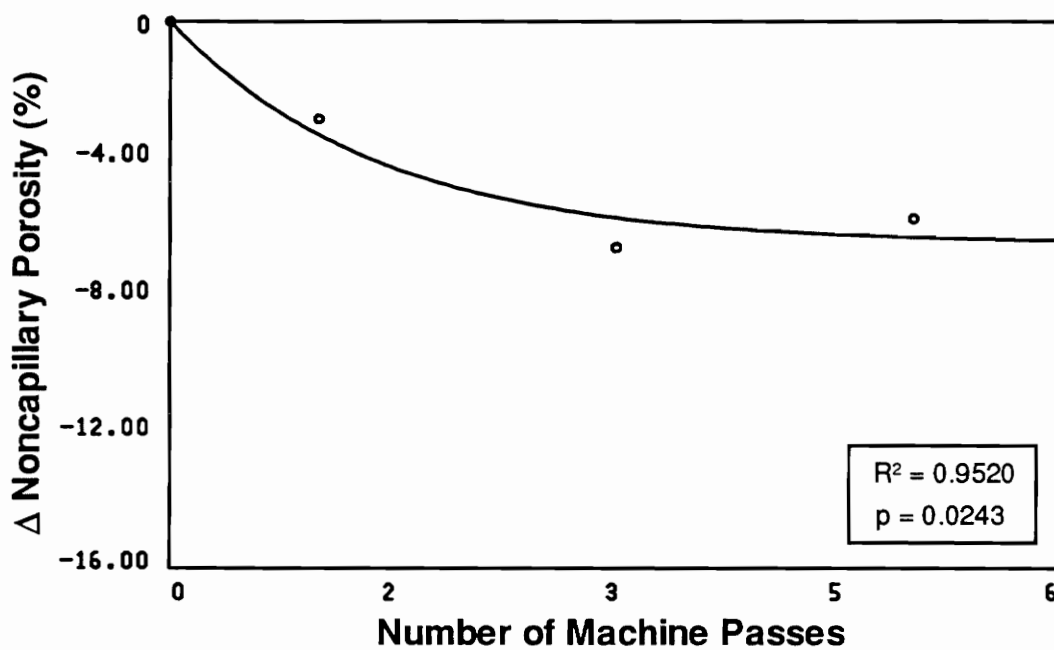


Figure 36. Live crop treatment noncapillary porosity response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = -9.261(1 - e^{-0.429X})$

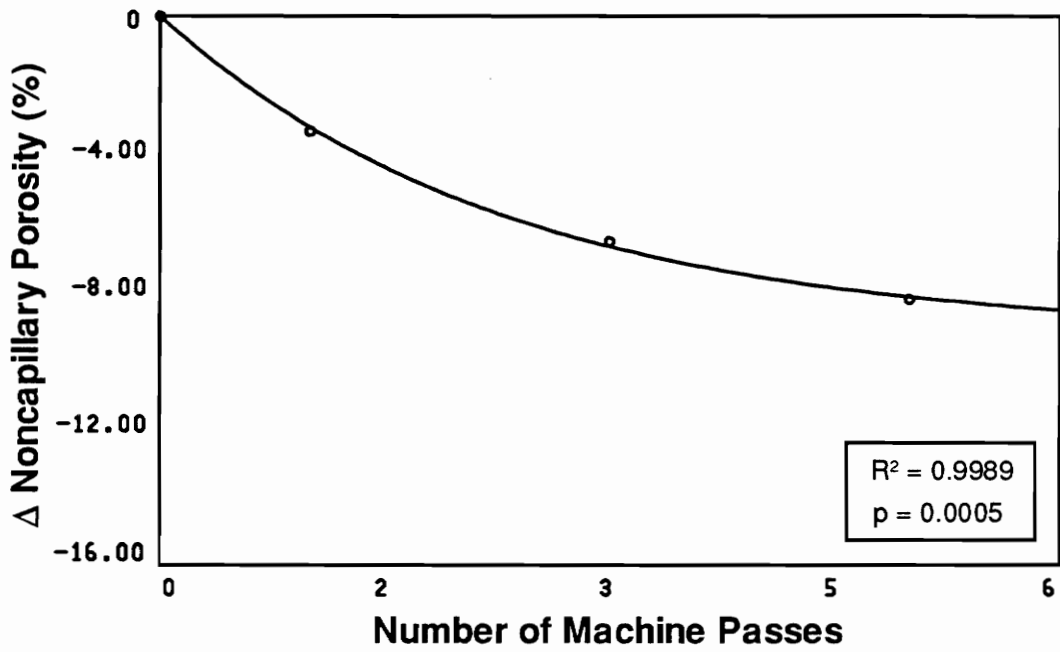


Figure 37. Live crop treatment noncapillary porosity response to machine traffic on the McGary soil (Block 2).

Equation: $Y = -7.121X^{0.324}$

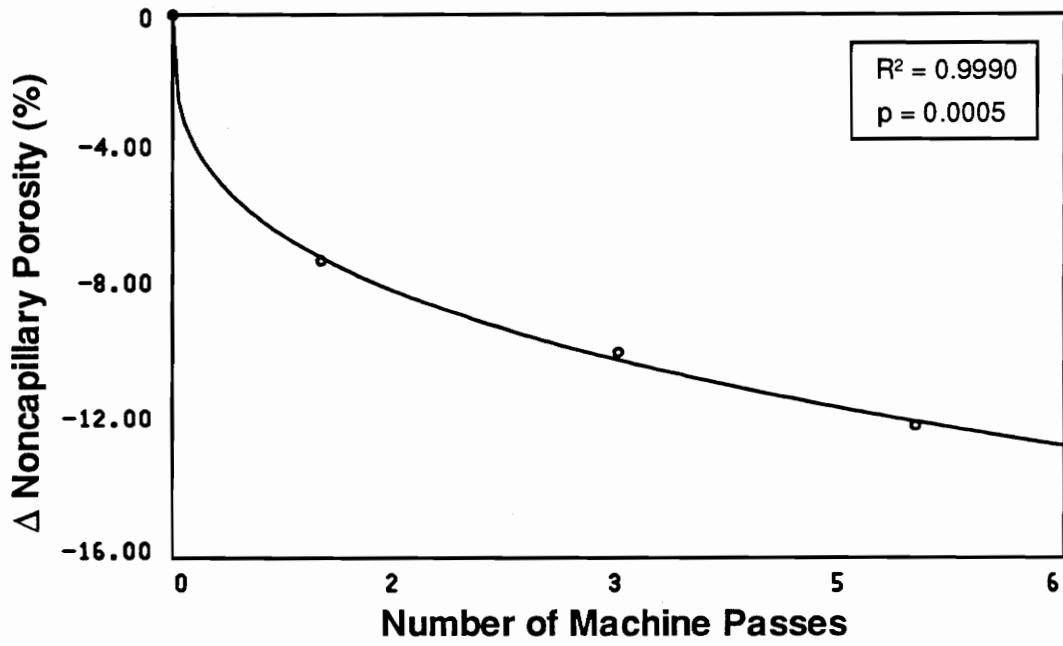


Figure 38. Desiccated treatment noncapillary porosity response to machine traffic on the Zoar soil (Block 1).

Equation: $Y = -9.757(1 - e^{-0.602X})$

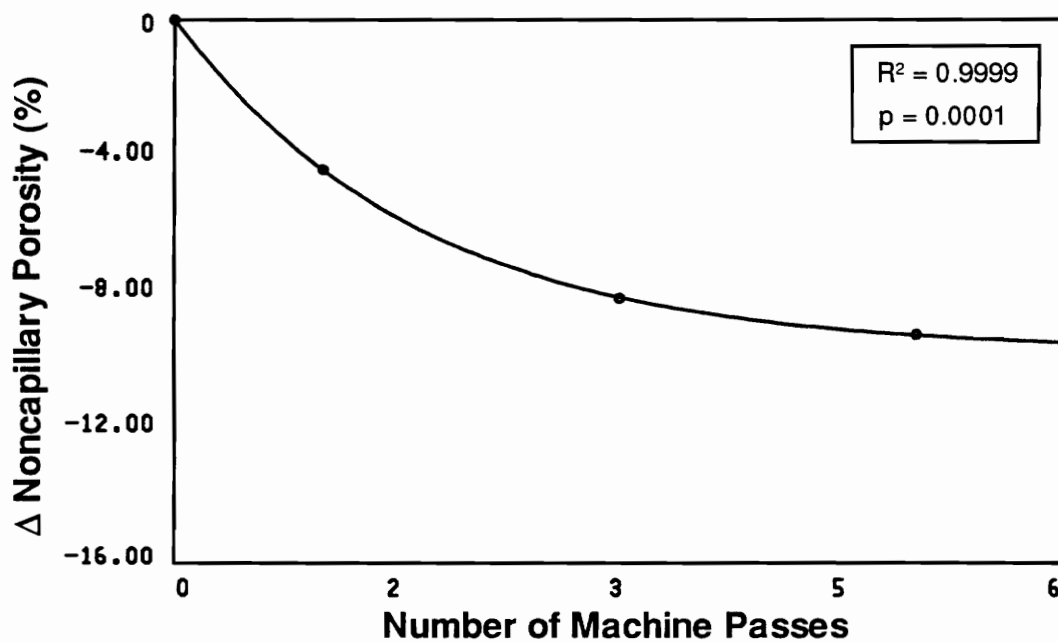


Figure 39. Desiccated treatment noncapillary porosity response to machine traffic on the McGary soil (Block 2).

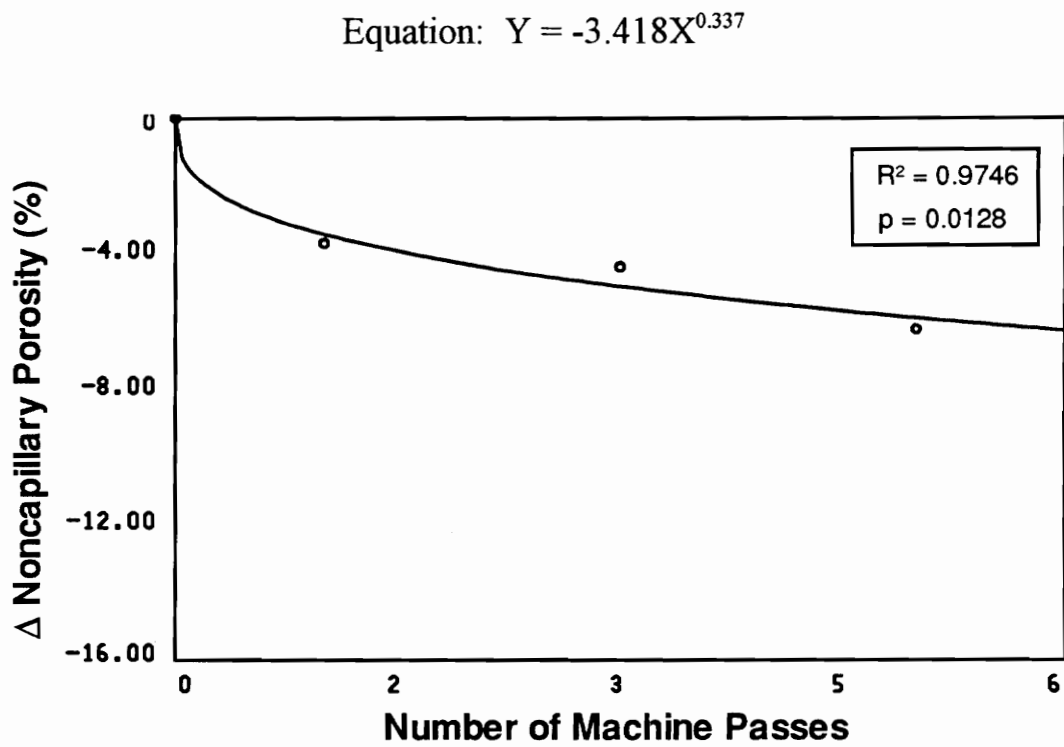


Figure 40. Residue-removed treatment noncapillary porosity response to machine traffic on the Zoar soil (Block 1).

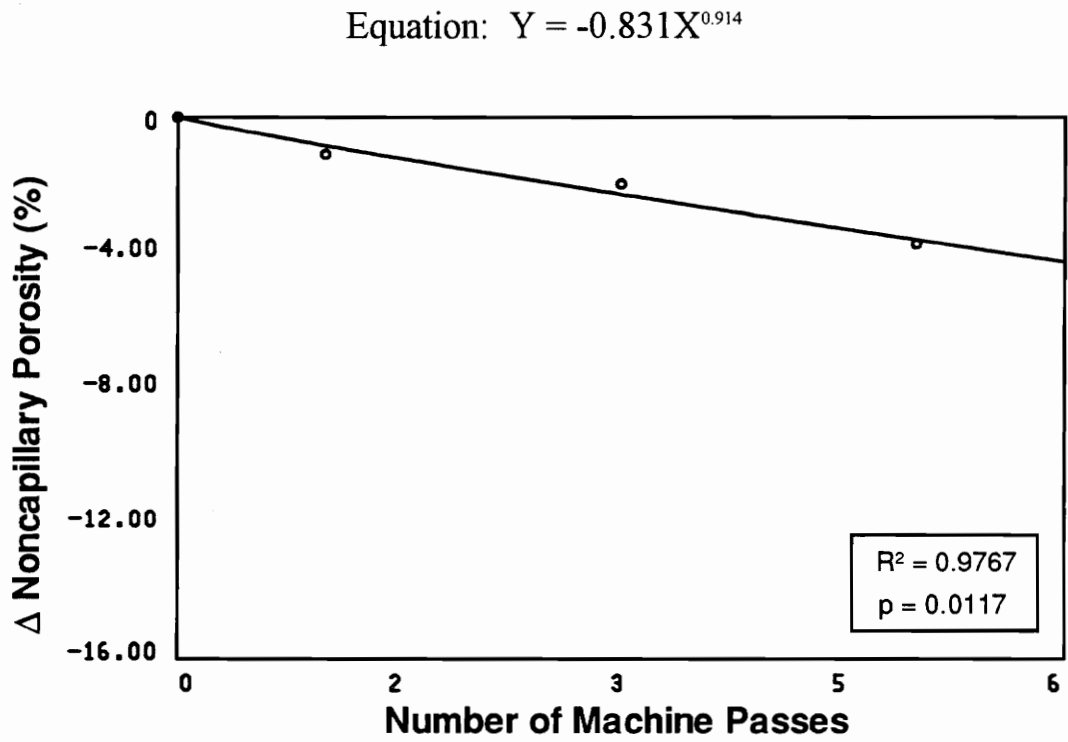


Figure 41. Residue-removed treatment noncapillary porosity response to machine traffic on the McGary soil (Block 2).

All of the fitted curves produced high R^2 values and each model was statistically significant. The fallow treatment response to machine traffic in Block 1 was well described by a growth curve such as that used for the bulk density response (Figures 18 and 34). Although capillary porosity for the block showed a clear increase between the three- and five-pass traffic levels (Figure 26), the noncapillary response was relatively flat. The fallow treatment in Block 2 responded to traffic in a manner similar to that of its bulk density and capillary porosity responses. There were steady decreases in noncapillary porosity through five machine passes (Figure 35). The fallow treatment suffered the largest loss of noncapillary porosity of any treatment.

Since noncapillary porosity values were based on two other measured quantities, it was only reasonable to expect correspondence among the measures. The relatively erratic behavior of the noncapillary porosity data for the live crop treatment in Block 1 (Figure 36) reflected that of both the bulk density and the capillary porosity data. The better-behaved data from Block 2 (Figure 37) were well fit by a growth curve, as were the corresponding bulk density and capillary data.

The perception of a breakdown in the protection against compaction effects by the desiccated treatment in Block 1 was reinforced by the noncapillary porosity data (Figure 38). There was a relatively large decrease in noncapillary porosity between the three- and five-pass traffic levels. The desiccated treatment experimental units in Block 2

experienced a more gradual rate of decrease in noncapillary porosity (Figure 39). The magnitude of change was smaller than that exhibited by the fallow treatment at the one- and three-pass traffic levels on both blocks.

The residue-removed treatment in Block 1 suffered little decrease in noncapillary porosity between the one- and three-pass traffic levels (Figure 40). A relatively large decrease resulted from traffic between the three- and five-pass levels, however. Block 2 sustained losses in noncapillary porosity that related in a linear fashion to the number of traffic passes (Figure 41). The behavior of the soil in the residue-removed plots in both blocks was similar to that exhibited in the capillary porosity response curves. However, the overall absolute magnitude of noncapillary porosity change was greater than that of capillary porosity for all treatments. Compaction results in a loss of total pore space, and noncapillary pores are more susceptible to compaction effects than are smaller pores.

Noncapillary Porosity - Subsurface Zone Results. Although the absolute magnitude of the variations among noncapillary porosity means was greater than that among capillary porosity means, there were no significant differences to report at any traffic level (Table 23). Subsurface moisture conditions produced the now familiar pairing effect on initial noncapillary porosity values. The level of within-treatment variability in the noncapillary porosity data prevented the declaration of statistically-significant differences, however.

Table 23. Noncapillary porosity means for each treatment and for each level of traffic pooled across blocks, subsurface zone (%).

Treatment	Number of Passes			
	0	1	3	5
Fallow	13.93*	14.13	12.44	13.49
Live Crop	12.53	13.76	12.02	12.48
Desiccated	15.03	14.09	14.79	12.89
Residue-removed	12.78	14.13	12.91	14.57

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

Initial noncapillary porosity means were significantly greater in the surface zone than in the subsurface soil zone for all treatments ($p = 0.0000$) (Table 20). It took only one machine pass to equalize surface- and subsurface-zone treatment means for the fallow and the live crop treatments. It took three passes to do the same in the desiccated plots. After five machine passes, the fallow treatment surface-zone noncapillary porosity mean was significantly lower than the subsurface-zone mean ($p = 0.0182$). Traffic effects on noncapillary porosity did not extend to the subsurface zone, however. Two-sample t-tests were performed to assess differences between traffic levels for the various treatments. There were no significant differences between conditions in the tracked areas and the zero-pass areas for any of the treatments at any level of traffic.

Effects on Noncapillary Porosity - Practical Significance. As noted in the review of the literature, maintenance of at least ten percent air-filled porosity in the root zone when a soil is at field capacity is an accepted requirement for plant development. Field capacity typically corresponds to a moisture tension of 10 kPa (Dexter, 1988). In this work, the tension table apparatus created a tension of 4.9 kPa. The use of ten percent air-filled porosity as a plant development threshold based on data developed at the lower tension level was a conservative measure. Fewer continuous pores would have been drained by the lower tension. The approach served to compensate for the effect of pore discontinuity within the soil matrix on air and water transmission.

Treatment performance was compared based on the conservative growth-limiting noncapillary porosity threshold. Noncapillary porosity in the surface zone of one of the fallow treatment replicates was driven beyond the threshold by one machine pass. After three machine passes, one fallow treatment replicate in each block had crossed the threshold. After five machine passes, two fallow treatment replicates in each block suffered from growth-limiting noncapillary porosity levels. Fully half of the fallow treatment replicates were adversely affected by five machine passes. Only one live crop treatment replicate in each block sustained similar damage. In Block 1, the condition occurred after three machine passes. In Block 2, it took five machine passes. Neither the desiccated nor the residue-removed treatment had even one replicate that crossed the established noncapillary porosity threshold.

The previous standard for judging practical significance could be vulnerable to dispute due to the limited depth in the soil at which the effects were measured. There is no dispute, however, regarding the effect of macropore loss on hydraulic conductivity. Saturated hydraulic conductivity for a soil profile is determined by the most restrictive layer, regardless of its position within the profile. Five machine passes produced a mean level of noncapillary porosity in the surface zone of the fallow plots that was significantly lower than that in the subsurface zone. Remember, too, that destruction of macropore surface connections at any level of traffic is tantamount to destruction of the macropores themselves.

This work confirmed the relationship between macroporosity and saturated hydraulic conductivity. Analysis of correlation between noncapillary porosity and K_{sat} produced a Pearson's $r = 0.6555$ and a Spearman's $\rho = 0.7747$. Spearman's rank correlation coefficient, ρ , measures the monotonic association between variables (Ott, 1988). The fact that ρ was greater than Pearson's more familiar r value indicated a nonlinear relationship between the variables. Regression analysis uncovered a rather strong relationship between K_{sat} and noncapillary porosity (in percent) raised to the fourth power. Standard regression techniques produced an R^2 value of 0.5928. Robust regression (Hintze, 1992b) produced an R^2 value of 0.7961. The relationship clearly illustrated the

potential for seriously affecting saturated hydraulic conductivity by destroying soil macropores.

Saturated Hydraulic Conductivity

The analysis of saturated hydraulic conductivity based on soil cores provided many challenges. Thorough analysis of data that do not follow a normal (Gaussian) distribution can be more complicated than analysis of normally-distributed data. Many observations of saturated hydraulic conductivity appeared to be quite large in comparison to published mean values and accepted standards of flow through loam soils (Klute and Dirksen, 1986). The source of such large values was virtually impossible to determine with certainty in most cases. Not knowing if high flux conditions resulted from porosity within the cores or from core disruption of some sort produced a particularly perplexing situation. *Was it preferable to have no data than data that were possibly tainted?* That question was never satisfactorily answered. Through the course of this work, the reasons why some researchers challenge the very use of small cores to determine K_{sat} (Rogers et al., 1985) became increasingly apparent.

The extreme variability of saturated hydraulic conductivity data was evident during the laboratory testing process. Some cores allowed a liter of water to percolate into the collection flask in a matter of minutes, while others took hours to produce one-tenth that

volume. The distinction between cores taken from undisturbed zones and those taken from tracked zones was normally quite obvious. It was only after the K_{sat} values were calculated and tabulated that the analytical challenges became obvious. Some data sets produced coefficients of variation that exceeded 100%.

The first step in the statistical analysis process was to identify the type of probability distribution that best described the data. This measure helped to determine appropriate analytical approaches for data that were treated in practice as lognormally-distributed. I used the distribution fitting routine VTFIT© (Cooke, 1993b) to analyze saturated hydraulic conductivity data from the uncompacted surface zones in the experiment sites. The blocks were analyzed separately to avoid contamination of the data by differences related to soil type.

Distribution fitting routines can produce erratic results when used with small samples of less than twenty data points (Hintze, 1992a). To assemble sufficient sample numbers to perform the statistical test, fallow and desiccated treatment data were pooled. Live crop and residue-removed data were also pooled, thus providing two groups of 32 K_{sat} data points per block. Three of the data sets showed excellent conformance to the lognormal distribution (chi-square p values ranged from 0.7765 to 0.9985). The set that included data from the live crop and residue-removed treatments in Block 2 did not conform to the lognormal distribution ($p = 0.0995$). The normal distribution produced an abysmal fit ($p =$

0.00004). The data were best described by a Gumbel asymptotic extreme-value distribution ($p = 0.4471$). In subsequent analyses, all data were treated as non-normal.

In spite of the conviction that the data were not normally distributed, and the knowledge that lognormal and Gumbel data could take on extreme values, some of the conductivity data were so large as to cause alarm (300 to 600 cm/h). *Were these valid data points or were they outliers?*

An outlier has been defined as *an observation (or subset of observations) which appears to be inconsistent with the remainder of that set of data* (Barnett and Lewis, 1984).

Although there were a number of measured conductivity values from both soil blocks that exceeded 200 cm/h, a measurement of 627 cm/h stood apart from the rest of the data. Identification of outliers is often a matter of subjective judgment on the part of the observer. Some contend that there can be no true outliers in measured hydraulic conductivity in the presence of preferential flow paths such as biopores. Although large biopores were avoided when soil core samples were extracted, many cores were quite porous throughout.

All soil cores were examined subsequent to oven drying. Any core that produced noticeably high conductivity was thoroughly examined to determine the cause(s) of the high flow condition. The source of extreme values, so critical to their proper handling,

was often impossible to ascertain. Some cores with no apparent irregularities produced large K_{sat} values. Some cores in questionable condition produced perfectly ordinary flow. In the case of the one unmistakably extreme value, flow at the core boundary *appeared* to be the source of the extraordinary measured conductivity.

The data sets were examined by a soils expert in the Virginia Tech College of Forestry, Dr. Michael Aust. He expressed concern at the presence of measured conductivity values that were in excess 100 cm/h. Dr. Aust suggested that the offending values be discarded since they represented pipe flow through large pores, or flow at the soil core-sampler liner interface, rather than conductivity through the soil matrix. It was then that a formal method of identifying aberrant values in the data sets for the treatments was sought. The ability to successfully identify the largest extreme value as an outlier was used as the criterion for judging the usefulness of any formal identification procedure. If a rational basis for rejecting this "tainted" value could be found, it would be applied throughout the data set to systematically remove the effects of more subtle offenders.

Dixon (1986) presented the method for identifying and dealing with discordant values in soil property data that was used in this experiment - the *Q test*. The straightforward procedure simply compares the distance of a doubtful observation from its nearest neighbor to the difference between the greatest and least value in that data set. For a set of n observations, the ratio Q is defined as follows:

$$Q = \frac{x_2 - x_1}{w}$$

or

$$Q = \frac{x_n - x_{n-1}}{w}$$

where

w = the range of a set of observations, $w = x_n - x_1$.

The range is a highly-efficient measure of dispersion for data sets with ten or fewer observations. In this experiment, a set of observations, or population, was defined by its block, treatment, soil depth, and traffic level. For instance, there were eight observations from three-pass wheel tracks on the desiccated treatment from the Zoar soil surface layer.

Dixon (1986) provided critical values for the Q ratio defined at 80% and 90% confidence levels for populations numbering two to ten. If an extreme value, upper or lower, produced a Q ratio that exceeded the critical value, the value was replaced by the median of its population. The median was chosen as a substitute for outliers because it is a good measure of the central tendency of a population in which variables can take on extreme values (Law and Kelton, 1991).

The Q-test procedure resulted in the removal and replacement of 22 of 320 values in the surface-soil data set and 27 of 320 values in the subsurface-soil data set. The censored data represented both extreme low and extreme high values from the treatment populations. Although the procedure removed less than nine percent of either zone's original data points, the overall experimental results were noticeably altered. An indication of the gravity of the alteration was the fact that the rank order of treatment means was changed at every level of traffic for the surface zone. The unsettling nature of this result led to the adoption of an alternative analytical approach - *accommodation* of data with extreme values via transformation. In this case, geometric means were used to represent K_{sat} data from each level of traffic within each treatment replicate. Use of geometric means produced transformed data that were easier to interpret than logarithms, when presented alongside their original, untransformed counterparts.

I adopted the data presentation philosophy of Mead and Curnow (1983) for use with saturated hydraulic conductivity analysis in this work. In instances where rejection of "rogue" values alters statistical conclusions, the statisticians proposed the presentation of both altered and unaltered analyses. The reader is then left to judge which analysis is more likely to be correct. In this case, I have presented analyses based on three versions of the hydraulic conductivity data for the reader's approval: the original, unaltered data set; the set in which outliers were identified and replaced; and the transformed version of the original data set. In addition, I have presented both ANOVA results, supplemented by

Fisher's LSD designations where appropriate, and results of Friedman's two-way layout tests for all the data.

Surface Zone Results. The initial pairing of treatments seen throughout the analysis of soil property data was evident in the saturated hydraulic conductivity results. In each of the three sets of results for the surface soil zone, the K_{sat} means for the fallow and the desiccated treatments were conspicuously greater than the means for the live crop and the residue-removed treatments (Tables 24 - 26). Only the data from which outliers had been removed produced an indication of significant differences among the zero-pass treatment means, however. This result was due to the fact that removal of outliers had reduced the mean square error (MSE) term to less than one-third of its original value. The zero-pass treatment mean square (MST) term was reduced by only 16 percent by the procedure. It is, therefore, easy to see why significant differences were reported in the ANOVA for the amended data and not for the original data. The Friedman two-way layout tests produced no indication of significant differences for any of the data sets at any level of traffic, pointing out shifts in ranks among the treatments from block to block. Given the initial pairings, and the similarities among means following tractor traffic, it was not surprising that some shifting among the ranks of means took place, given the high degree of variability in the data. In spite of the failure of the Friedman tests to indicate significant treatment differences, there was no statistically significant block-treatment interaction for any of the data based on ANOVA results.

Table 24. Saturated hydraulic conductivity means for each treatment and for each level of traffic pooled across blocks, surface zone (cm/h).

Treatment	Number of Passes			
	0	1	3	5
Fallow	101.7	22.2	5.5	4.9
Live Crop	45.5	21.9	4.9	6.2
Desiccated	104.1	24.3	17.8	5.4
Residue-removed	53.3	24.2	19.2	7.1
ANOVA p-value	0.151	0.996	0.257	0.921
Friedman p-value	0.167	1.000	0.208	0.625

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

The original data show distinct pairings at the zero-pass traffic level and very good agreement between paired treatment means. One tractor pass produced essential equality among the treatment means. The Friedman test result, $p = 1.000$, indicated that the treatment rankings had changed completely from Block 1 to Block 2. By the third tractor pass, K_{sat} means for the fallow and the live crop treatments had fallen to a (numerically) lower level than the desiccated and the residue-removed treatment means. The final tractor passes produced essentially equivalent hydraulic conductivity means for all of the treatments.

Table 25. Saturated hydraulic conductivity means for each treatment and for each level of traffic pooled across blocks, surface zone, amended data (cm/h).

Treatment	Number of Passes			
	0	1	3	5
Fallow	76.0 a*	22.2	2.0 c	1.5 b
Live Crop	38.5 b	15.8	4.9 bc	4.1 ab
Desiccated	92.9 a	24.3	8.3 ab	5.4 a
Residue-removed	34.8 b	15.1	9.1 a	6.5 a
ANOVA p-value	0.006	0.737	0.011	0.076
Friedman p-value	0.167	0.958	0.167	0.375

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

By comparing Tables 24 and 25, it is clear that all of the zero-pass, two of the one-pass and three each of the three- and five-pass treatment means were affected by the removal of outliers. Analysis of variance produced significance in the amended data at three levels of traffic where there was none for the original data.

The amended data revealed consistent, traffic-related trends in the saturated hydraulic conductivity means for all treatments. Analysis of variance of zero-pass means showed the fallow and the live crop treatment means to be significantly higher than the live crop and the residue-removed treatment means. This result was consistent with that from

noncapillary porosity analysis. One machine pass produced treatment means that could not be judged significantly different, but which still showed signs of differences between the two treatment pairs. Following the third machine pass, statistically-significant differences among the treatments, based on ANOVA, reappeared. The fallow treatment mean was lower than that of either the desiccated or the residue-removed treatment. The live crop treatment mean was not statistically different from either the desiccated or the fallow mean, however. All means were reduced between the three-pass and the five-pass traffic levels. The statistical groupings remained essentially intact between the two traffic levels.

Table 26. Saturated hydraulic conductivity means for each treatment and for each level of traffic pooled across blocks, surface zone, based on pooled geometric means (cm/h).

Treatment	Number of Passes			
	0	1	3	5
Fallow	81.5	10.3	2.7	2.4
Live Crop	33.8	16.6	4.1	3.5
Desiccated	83.0	17.0	13.6	4.8
Residue-removed	33.6	19.4	13.7	5.9
ANOVA p-value	0.120	0.748	0.178	0.397
Friedman p-value	0.208	0.375	0.167	0.625

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

The pairings noted in the analysis of the amended zero-pass data were evident in the transformed data as well. The trend of reduced saturated hydraulic conductivity resulting from increased traffic was consistent among the treatments. The drop in K_{sat} measured for the fallow treatment following one tractor pass appeared much larger in the transformed results than in the amended results. The fallow treatment produced the (numerically) lowest K_{sat} means from the one-pass traffic level on. However, analysis of the transformed data produced no evidence of statistically-significant treatment differences at all.

Based on a consensus of analytical results, it can be stated, unequivocally, that there were no significant differences among saturated hydraulic conductivity means after one tractor pass. Whatever differences that might have existed initially were eliminated by the first pass. After three passes, the desiccated treatment K_{sat} mean was superior to the fallow treatment mean in all analyses. However, all treatments suffered large measured reductions in surface-zone saturated hydraulic conductivity due to five machine passes. The numerical differences between the fallow treatment mean and the cover-cropped treatment means did not produce consistent statistical significance. Further interpretation is left to the reader.

Subsurface Zone Results. Treatment means and results of statistical analysis of saturated hydraulic conductivity data for the subsurface-zone soil are presented in Tables

27 - 29. Based on comparisons of zero-pass treatment means for the surface and subsurface soil zones, the subsurface-zone soil was clearly more limiting to hydraulic conductivity through the soil profile than the surface-zone soil. Initial subsurface-zone K_{sat} means were significantly lower than surface-zone means for all treatments in each data set. After one machine pass, only the desiccated treatment had a surface-zone conductivity mean that could be judged greater than its subsurface-zone mean for each data set. Outliers in the original one-pass and five-pass data were all that prevented the same declaration for the live crop treatment at all levels of traffic.

Table 27. Saturated hydraulic conductivity means for each treatment and for each level of traffic pooled across blocks, subsurface zone (cm/h).

Treatment	Number of Passes			
	0	1	3	5
Fallow	12.8	14.8	8.6 ab*	13.6
Live Crop	4.0	28.0	1.7 c	2.6
Desiccated	14.5	9.0	11.5 a	12.0
Residue-removed	15.6	9.2	5.6 bc	19.4
ANOVA p-value	0.519	0.605	0.008	0.137
Friedman p-value	0.375	0.833	0.167	0.375

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

Analysis of the original data revealed no clear patterns in treatment responses to machine traffic. The ANOVA-LSD indication of significantly-different treatment means at the three-pass traffic level was not reflected in the Friedman test results.

Table 28. Saturated hydraulic conductivity means for each treatment and for each level of traffic pooled across blocks, subsurface zone, amended data (cm/h).

Treatment	Number of Passes			
	0	1	3	5
Fallow	7.4 b*	7.2	8.6 ab	11.4 a
Live Crop	1.8 c	6.3	0.9 c	1.5 b
Desiccated	13.3 a	5.7	9.4 a	10.0 a
Residue-removed	1.9 c	4.5	5.2 b	8.6 a
ANOVA p-value	0.002	0.624	0.004	0.090
Friedman p-value	0.167	0.958	0.375	0.458

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

Just one treatment mean, that of the fallow treatment at the three-pass traffic level, was unaffected by the removal and replacement of outliers. Partly as a result, the analysis of the amended subsurface-zone conductivity data produced indications of significant treatment differences at the zero-, three-, and five-pass traffic levels. There were, however, no other similarities between surface-zone and subsurface-zone results. The

only consistent traffic-related trend in the data was the increase in K_{sat} exhibited by the residue-removed treatment. In fact, two-sample t-tests revealed significant differences between the zero-pass and the five-pass residue-removed treatment means for both soil blocks.

Table 29. Saturated hydraulic conductivity means for each treatment and for each level of traffic pooled across blocks, subsurface zone, based on pooled geometric means (cm/h).

Treatment	Number of Passes			
	0	1	3	5
Fallow	6.4	8.2	4.9 ab*	6.8 ab
Live Crop	2.1	5.0	1.4 b	1.6 b
Desiccated	6.3	5.7	7.8 a	3.7 b
Residue-removed	2.3	5.7	3.7 b	11.4 a
ANOVA p-value	0.129	0.744	0.058	0.066
Friedman p-value	0.208	0.833	0.042	0.375

*Means within a column followed by the same letter are not significantly different by Fisher's F-protected LSD, $\alpha = 0.10$. Columns with no letters have no significant differences among treatments.

As was the case with soil porosity, saturated hydraulic conductivity sampled in the uncompacted areas was affected by pre-test treatment effects on subsurface-zone moisture content. There were differences among the treatments initially. In the results from the amended and the transformed data, the familiar pairing of treatment means was evident.

Only in the analysis of the amended data set were the zero-pass means judged significantly different, and then, only by ANOVA. The subsurface soil that did not suffer drying-induced compaction in the field (Table 10) produced a higher level of saturated hydraulic conductivity in the laboratory.

There was, for the transformed data, seemingly random variation in the subsurface-zone saturated hydraulic conductivity from one traffic level to another. The consistent trend seen in the amended residue-removed treatment means was not repeated in the transformed data. For the only time in the analysis of treatment effects on saturated hydraulic conductivity, both the ANOVA and Friedman test results indicated significant differences among the transformed treatment means at the three-pass traffic level (Table 29). Based on the nonparametric multiple comparison test, the live crop and desiccated treatment means could be declared significantly different. However, the difference did not persist through five machine passes.

Physical Significance. The interpretation of the statistical significance of treatment effects on soil response to machine traffic was less than straightforward. There were seemingly large numerical differences in saturated hydraulic conductivity among the treatments that failed to translate into statistical differences. To assist in putting the K_{sat} values into some physical perspective, Table 30 provides a range of hydraulic conductivities used for field classification of soil (Ghildyal and Tripathi, 1987):

Table 30. Hydraulic conductivity classes for saturated soils (cm/h).

Class	Hydraulic Conductivity
Very Slow	< 0.125
Slow	0.125 - 0.5
Moderately slow	0.5 - 2.0
Moderate	2.0 - 6.25
Moderately rapid	6.25 - 12.5
Rapid	12.5 - 25.0
Very rapid	> 25.0

Hydraulic conductivities measured from soil cores tend to exceed measurements taken *in situ*. However, the tabulated ranges provide a measure of the degree of traffic effects on this important soil property. Initially, all treatments exhibited very rapid hydraulic conductivity through the surface zone. Even after one tractor pass, mean conductivity remained rapid through soil cores taken from all cover-cropped treatments. Further traffic led to numerical differences among the treatment means, but no treatment suffered consistently slow hydraulic conductivity as a result of machine traffic.

In most comparisons among the data sets, the subsurface zone appeared more limiting to measured conductivity than the surface zone. Only at the three- and five-pass levels was there evidence of the surface zone becoming more limiting to conductivity than the

subsurface zone due to traffic effects. The fallow treatment gave the clearest indication of traffic-related damage to surface-zone conductivity.

Biomass Yield Effects on Soil Response to Machine Traffic

It was hypothesized that a range of biomass yields would produce a correspondent range of soil reactions to machine traffic. Rye yields were measured near soil core sampling sites for the purpose of testing the hypothesis. Summaries of biomass yield results were presented in Tables 4 - 6. The error bar plots in Figures 42 and 43 provide graphical depictions of measured yield means and standard deviations. Each biomass yield is displayed as a small circle with a number inside to identify the treatment. Standard deviations are displayed as rays extending from above and below the mean.

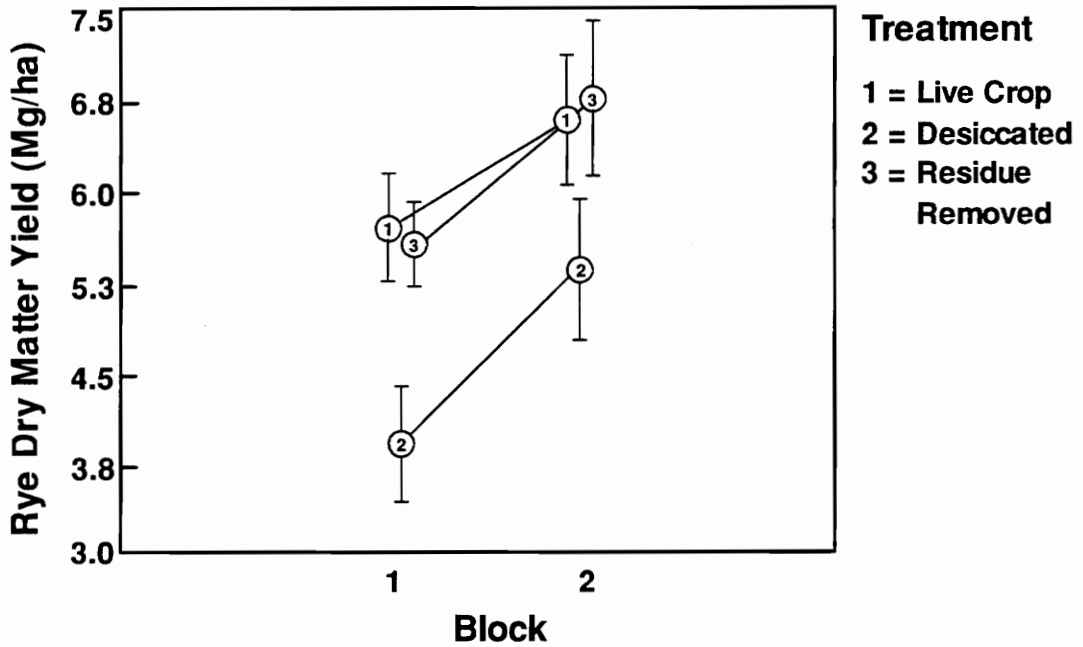


Figure 42. Rye crop dry matter yields from the first round of biomass sampling within cover-cropped treatment units.

The live crop and residue-removed treatment yield means were quite similar in both Blocks 1 and 2. The desiccated treatment yields suffered as a result of the time lag between herbicide application and yield sampling. In the other treatment units, the crop continued to grow. There was a substantial yield difference between blocks for each treatment. However, the yields from both blocks were higher than the rye yields of between 2.4 and 3.9 Mg/ha normally recorded in Virginia (VCES, 1987).

As indicated by the rays in Figure 42, the standard deviations associated with measured yields were large. The variation, judged to be unrepresentative of yield conditions in the field, led to a second round of sampling.

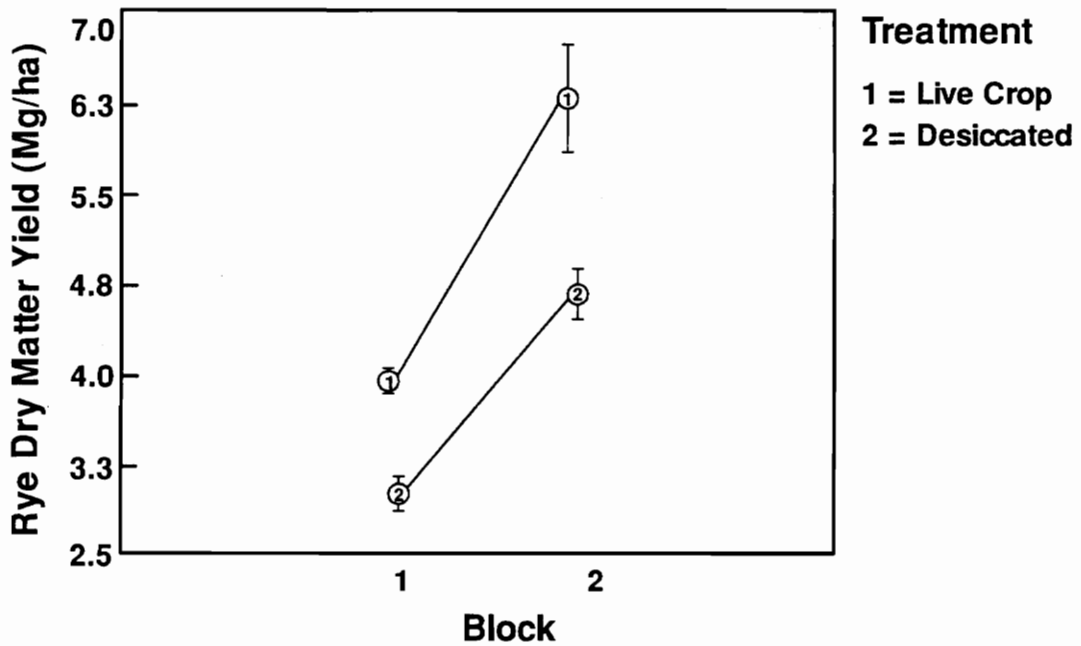


Figure 43. Rye crop dry matter yields from the second round of biomass sampling within cover-cropped treatment units.

The second set of samples, taken from the wheel tracks after soil core sampling, exhibited less variation than the first set. The relatively large standard deviation associated with the live crop yield in Block 2 was attributable to lodging that took place following the spring

application of nitrogen fertilizer. In spite of the reduction in fertilizer application rate (56 kg N/ha versus the scheduled 78.5 kg N/ha), the rye crop on the river terrace responded with vigorous vegetative growth, producing lodging in the live crop plots. The resulting random arrangement of standing and fallen rye plants produced a non-uniform mat of vegetation in the tractor wheel tracks. The desiccated crop was affected less by lodging due to the timing of growth suppression. Both treatments on the lower-yielding upland site were unaffected by lodging.

The yield ranges measured *within* blocks, from either round of sampling, were insufficient to produce detectable effects on soil response to machine traffic. Whether the lack of response resulted solely from yield similarities, or from an interaction between crop yield and moisture content, could not be determined from the data. However, there was positive correlation, in both blocks between crop yield and surface-zone soil moisture content (Table 31).

Table 31. Correlation coefficients between rye biomass yield and soil moisture content for two cover-cropped treatments, by block.

Treatment	Block	Correlation Coefficient	
		Pearson's r	Spearman's ρ
Live Crop	1	0.3444	0.3572
	2	0.3782	0.5814
Desiccated	1	0.7535	0.4526
	2	0.5329	0.5814

The measured moisture content at most core sampling sites was below the optimum moisture content for compaction. Therefore, positive correlation between biomass yield and moisture content meant that as the level of biomass available for cushioning the impact of the tractor wheel increased, so too did the compactibility of the soil.

Treatment response curves for bulk density, capillary porosity, and noncapillary porosity (Figures 18-41) provided indications of interblock crop yield effects on soil response to machine traffic. The higher-yielding rye of Block 2 appeared to provide a greater measure of protection against soil compaction than that of Block 1. Soil textural differences between the blocks served to enhance the perceived effect of crop yield. The McGary soil, with its higher clay content, simply responded more gradually than the Zoar soil to the repeated short-duration loads imposed by wheel traffic. However, treatment responses were found to vary not only by traffic level, but by soil property category, as well. The

effect of biomass yield was not large enough in all cases to overcome the effects of other variables that affected soil response.

The fact that the hypothesized relationship between biomass yield and soil response to machine traffic failed to materialize was not particularly surprising. Gupta et al. (1987) failed to find a yield effect when corn residues were present on the soil surface at levels ranging from 0 to over 10 Mg/ha. Of course, plants can contribute more than just surface residues to reduce the effects of machine-induced soil compaction.

Conclusions

The fundamental lesson to be learned from the field and laboratory research results reported in this work is that cover crop treatments produce a series of related changes in the soil-plant microenvironment. Factors of tremendous importance to machine-soil interaction such as moisture content and soil bulk density are affected in interrelated ways by the very culture of cover crops.

Differences in initial soil property conditions among the treatments prevented equitable comparisons of all treatment combinations. However, similarities in initial conditions between two pairs of treatments allowed direct comparison of treatment performance for each pair. The performance of the cover-cropped treatment in which above-ground plant material was desiccated could be directly compared to the performance of the fallow control treatment. Comparison of the other cover-cropped treatments provided an opportunity to assess the relative contributions of above-ground biomass and plant roots to the alteration of soil response to machine traffic. The field experiment was supported by laboratory analyses of soil properties that aided the interpretation of experimental results.

The experiment involved a versatile crop that is grown not only for ground cover, but for grain and silage as well. The physical properties of the plants represented those of

agricultural crops, rather than forest crops - the source of most available data on plant alteration of machine-soil interaction. The tractor used to load the soil was sized to reflect the row-crop tractors that populate farms in the mid-Atlantic region, rather than those used in the Corn Belt. The above-ground biomass present in the desiccated and live crop treatments was intact and anchored by roots to the soil. The plant roots in each cover-cropped treatment were undisturbed by any mechanical manipulation. The experiment was conducted in a field setting where the full range of plant-soil interactions combined to produce a set of alternative treatments, indicative of actual field conditions.

Based on the research results analyzed in this work, the following statements can be made:

1. Cover crop cultural practices and treatment alteration of the soil moisture balance affected the initial status of all of the soil properties that were used as measures of treatment performance. The soil properties included:

- dry bulk density
- capillary porosity
- noncapillary porosity
- saturated hydraulic conductivity

2. Statistically-significant changes in measured soil properties resulting from tractor traffic were limited to a depth in the soil of less than 15 cm.
3. One pass of a wheel-type tractor was sufficient to produce statistical equality among the soil physical properties used to compare treatment performance.
4. Multiple tractor passes in the same wheel track produced soil responses that permitted statistical separation of treatment performance.

5. Multiple tractor passes in the same wheel track produced statistically-significant differences in measured dry bulk density and in noncapillary porosity within the surface zone (0 - 7.5 cm) of the soil.
6. Multiple tractor passes in the same wheel track produced no statistically-significant differences in treatment performance as measured by capillary porosity.
7. The condition of above-ground rye biomass affected soil moisture conditions and the resultant effects of machine traffic.
8. The biomass produced by the rye cover crop was not sufficient to cause statistically-significant performance improvements when compared to a treatment that included only undisturbed cover crop roots.
9. There was no statistically-significant evidence of treatment-soil type interaction effects on dry bulk density, capillary porosity, or noncapillary porosity.

Variability within the saturated hydraulic conductivity data prevented the development of any meaningful conclusions regarding treatment effects. Positive correlation between cover crop biomass yield and soil moisture content served to mask any effects of biomass yield on soil response to machine traffic. Differences in initial soil conditions between the live crop and the desiccated cover crop treatments prevented the direct assessment of the effect of cover crop condition on machine-induced soil compaction. The combination of desiccated above-ground biomass and intact roots provided some level of protection against all measured effects of machine-induced soil compaction.

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Appendix A. Soil Characterization Data

Virginia Tech Research Farm at Whitethorne

Compiled by Marc Crouch, Pam Thomas, Bill Edmonds, and Dan Ess

Soil type: McGary silt loam, 0 to 2 percent slopes

Date: 12 August 1992; MHC, WJE, PJT

Location: About 1.74 miles southwest 232° of the junction of VA-652 and VA-655 at Longshop and 1.38 miles south 190° of Wake Forest Cemetery on Whitethorne Farm, Montgomery County

Latitude: 37° 12' 24" N

Longitude: 80° 35' 31" W

Physiography: Ridge and Valley

Landscape position: River terrace

Native vegetation: Hay

Parent material: Alluvium

Slope gradient: 1 percent

Complexity: Simple

Aspect: N/A

Relief: 30 feet

Elevation: 1,700 feet

Erosion class: Slight

Internal free water: Thick perched water table, shallow, persistent

Drainage: Poorly drained

Flooding: Rare

Soil moisture: Moist (Colors are for moist samples.)

Root restricting depth: 60 inches

Rock fragments on the soil surface: None

Bedrock outcrops: None

Ap--0 to 11 inches; dark brown (10YR 3/3), broken, loam; moderate medium and coarse granular structure; friable, sticky, plastic; few very fine roots; many medium tubular pores; 2 percent rounded and subrounded chert, feldspar, and quartz gravel; slightly acid; abrupt smooth boundary.

Ac--11 to 19 inches; very dark grayish brown (10YR 3/2), broken, silty clay loam; strong medium and coarse granular structure; firm, sticky, plastic; very few very fine roots; common medium tubular pores; common medium irregular black (10YR 2/1), broken, manganese nodules and many coarse irregular yellowish brown (10YR 5/6), broken iron nodules; few fine flakes of mica; slightly acid; gradual wavy boundary.

Bt1--19 to 40 inches; yellowish brown (10YR 5/6), broken, silty clay; many coarse prominent gray (10YR 5/1), broken, redox depletions on ped faces and in root channels; moderate medium and coarse prismatic parting to moderate coarse platy structure; firm, sticky, plastic; very few very fine roots in pores; many very fine and common medium and coarse tubular pores; many distinct very dark grayish brown (10YR 3/2), broken, clay films on faces of peds; many coarse irregular black (10YR 2/1), broken, and dark gray (N 4/0), broken, manganese nodules and common coarse irregular yellowish red (5YR 4/6), broken, iron nodules; few fine flakes of mica; neutral; diffuse smooth boundary.

Bt2--40 to 60 inches; yellowish brown (10YR 5/6), broken, clay loam; many coarse prominent light gray (N 6/0), broken, redox depletions on ped faces and in root channels; moderate medium and coarse prismatic parting to weak coarse and very coarse platy structure; varve planes in prisms; friable, sticky, plastic; very few very fine roots; many very fine and common medium and coarse tubular pores; many distinct very dark grayish brown (10YR 3/2), broken, clay films on vertical faces of peds and in root channels; common coarse irregular strong brown (7.5YR 4/6), broken, manganese coatings and yellowish red (5YR 4/6), broken, iron nodules; few fine flakes of mica; neutral; clear smooth boundary.

C--60 to 80 inches; dark yellowish brown (10YR 4/4), broken, and light brownish gray (10YR 6/2), broken, loam; massive; friable, slightly sticky, slightly plastic; common fine vesicular pores; common medium irregular very dark gray (N 3/0), broken, manganese nodules; common fine flakes of mica; neutral.

Table A. Particle-size distribution

Depth	Sand						Silt	Clay
	VC	C	M	F	VF	Total		
in.	g kg ⁻¹ of soil							
0-11	36	45	54	101	85	320	463	217
11-19	82	28	11	26	45	192	416	392
19-40	1	4	6	59	73	143	456	401
40-60	0	3	2	74	120	200	501	299
60-80	0	7	14	162	259	443	385	173

Table B. Chemical Properties

Depth	NH ₄ OAc, pH 7, Extractable			H ⁺	Al ³⁺
	Ca ²⁺	Mg ²⁺	K ⁺		
in.	cmol _c kg ⁻¹ of soil				
0-11	5.46	1.20	0.13	7.60	0.10
11-19	9.20	1.78	0.12	5.20	0.10
19-40	7.24	2.30	0.10	1.60	0.10
40-60	4.92	1.90	0.07	1.00	0.10
60-80	6.89	2.60	0.09	1.60	0.10

Table C. Chemical Properties.

Depth	OM	pH	NCEC
inches	percent		cmol _c kg ⁻¹
0-11	1.94	6.25	9.50
11-19	1.16	6.52	14.10
19-40	0.35	6.60	11.50
40-60	0.12	6.70	8.90
60-80	0.17	6.70	8.70

Table D. Bulk density at field moisture and oven dry

Depth	D _o fm ^a	D _o od ^b
inches	g cm ⁻³	
0-11	1.60	1.63
11-19	1.62	1.69
19-40	1.67	1.69
40-60	1.58	1.64
60-80	1.57	1.65

^aBulk density at field moisture. ^bBulk density oven dry.

Soil type: Zoar loam

Date: 23 May 1994; WJE, DRE

Location: About 1.80 miles southwest 240° of the junction of VA-655 and VA-652 at Longshop and 2.12 miles north 10° of the junction of VA-623 and VA-600 on Whitethorne Farm, Montgomery County

Latitude: 37° 11' 47" N

Longitude: 80° 34' 12" W

Physiography: Ridge and Valley

Landscape position: River terrace tread

Native vegetation: Fallow

Parent material: Alluvium

Slope gradient: 1 percent

Complexity: Simple

Aspect: N/A

Relief: 30 feet

Elevation: 1,730 feet

Erosion class: Slight

Internal free water: Deep

Drainage: Moderately well drained

Flooding: None

Soil moisture: Moist (Colors are for moist samples.)

Root restricting depth: *

Rock fragments on the soil surface: 5 to 40 %

* Rock fragments prevented observation of the soil to 72 inches.

Ap--0 to 10 inches; dark brown (10YR 4/3), broken, loam; medium fine granular structure; moderately friable, slightly sticky, slightly plastic; moderate very fine roots; moderate very fine pores; 5 percent rock fragments; strongly acid; clear smooth boundary.

Bt1--10 to 30 inches; yellowish brown (10YR 5/6), broken, clay loam; fine moderate subangular blocky structure; moderately friable, slightly sticky, slightly plastic; common very fine roots; moderate very fine pores; 25 percent rock fragments; moderately acid; diffuse smooth boundary.

Bt2--30 to 34 inches; yellowish brown (10YR 5/6), broken, clay loam; fine moderate subangular blocky structure; moderately friable, slightly sticky, slightly plastic; common very fine roots; moderate very fine pores; 25 percent rock fragments; very strongly acid.

2Bt3--34 inches; Auger refusal (cobble or stone bed).

Table A. Particle-size distribution

Depth	Sand						Silt	Clay
	VC	C	M	F	VF	Total		
in.	g kg ⁻¹ of soil							
0-10	31	48	104	149	92	424	458	118
10-30	30	50	88	123	89	380	402	217
30-34	62	56	74	112	93	397	364	239

Table B. Chemical Properties

Depth	NH ₄ OAc, pH 7, Extractable			H ⁺	Al ³⁺
	Ca ²⁺	Mg ²⁺	K ⁺		
in.	cmol _c kg ⁻¹ of soil				
0-10	1.88	0.62	0.38	8.00	0.10
10-30	3.07	0.72	0.29	6.80	0.45
30-34	1.67	0.73	0.29	8.00	1.65

Table C. Chemical Properties.

Depth	pH
inches	
0-10	5.52
10-30	5.63
30-34	5.04

Appendix B. Precipitation Data

Virginia Tech Research Farm at Whitethorne

Precipitation Data - Whitethorne Farm, July - December 1992

Precipitation ¹						
	July	August	September	October	November	December
1	0.51	0.00	0.00	0.00	0.08	0.00
2	0.18	0.00	0.00	0.00	1.47	0.00
3	0.25	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	1.88	2.13	0.00	0.00
5	0.00	0.00	0.61	0.00	0.00	0.00
6	0.64	0.00	0.00	0.00	0.00	0.00
7	0.00	0.28	0.00	0.00	0.00	0.00
8	0.18	0.15	0.48	0.00	0.00	0.00
9	0.00	0.00	0.41	1.60	0.00	0.00
10	0.00	0.00	0.58	0.00	0.00	1.96
11	0.00	0.05	0.00	0.13	0.00	0.00
12	0.00	0.00	0.00	0.00	1.50	0.00
13	0.00	1.78	0.00	0.00	0.20	0.00
14	0.00	0.08	0.00	0.00	0.00	0.00
15	0.20	0.18	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	2.13
17	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.94
20	0.00	0.00	0.00	0.00	0.30	0.00
21	1.80	0.00	0.00	0.00	0.56	0.00
22	1.22	0.00	0.00	0.00	3.20	0.00
23	1.93	0.00	0.00	0.00	0.00	1.12
24	2.46	0.00	0.00	0.33	0.71	0.00
25	0.08	1.73	0.00	0.00	1.27	0.00
26	0.66	0.10	0.00	0.00	0.15	0.00
27	1.50	0.18	1.65	0.00	0.00	0.00
28	0.00	1.75	0.84	0.00	0.00	0.97
29	0.00	0.00	0.00	0.00	0.00	0.08
30	0.00	0.00	0.00	0.89	0.00	0.00
31	0.28	0.00	--	0.58	--	0.00
Total	11.89	6.28	6.45	5.66	9.44	7.20

¹ Precipitation measured in centimeters.

Precipitation Data - Whitethorne Farm, January - June 1993

Precipitation ¹						
	January	February	March	April	May	June
1	0.00	0.00	0.00	0.81	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.79	0.00	0.00	0.00
4	0.00	0.00	4.09	0.00	1.14	0.00
5	1.83	0.00	0.08	1.32	0.00	1.42
6	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00
8	2.44	0.00	0.08	0.00	0.00	0.00
9	0.56	0.00	0.20	0.66	0.13	0.00
10	0.13	0.00	0.00	0.00	0.00	0.00
11	0.51	0.00	0.00	0.00	0.10	0.00
12	0.28	1.02	0.00	0.00	0.36	0.00
13	0.08	0.00	1.04	0.00	0.51	4.32
14	0.00	0.00	0.00	0.00	1.75	--
15	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	1.52	0.00	2.11	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.86	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00
21	2.64	2.54	0.58	1.22	0.00	0.00
22	0.00	0.38	0.00	0.00	0.00	0.00
23	0.00	0.00	1.45	0.00	0.00	0.00
24	0.81	0.00	4.09	0.00	0.38	0.00
25	0.00	0.00	0.74	0.00	0.00	0.00
26	0.00	0.94	0.00	1.32	0.00	0.00
27	0.00	0.00	2.26	0.00	0.00	1.12
28	0.00	0.00	0.99	0.00	0.00	0.00
29	0.00	--	0.00	0.00	0.00	0.36
30	0.00	--	0.00	0.00	0.00	0.00
31	0.00	--	0.25	--	0.76	--
Total	9.28	6.40	16.64	7.44	5.99	7.22

¹ Precipitation measured in centimeters.

Vita

Dan Ess was born in Paris, Missouri on October 9, 1961. His parents, George and Marian Ess, still reside in Paris. Dan and his wife, Donna, have two children, Kathryn and Quincy. Dan graduated from Paris RII High School and from the University of Missouri-Columbia. He received Baccalaureate degrees in Agricultural Engineering and Agricultural Mechanization. After a four-year association with the family farm equipment dealership, Dan returned to school, this time at Virginia Tech. Over five years, he received a Master of Science degree, served as a full-time lecturer, and received a Doctor of Philosophy degree in Agricultural Engineering. Accompanied by his wife and children, Dan will begin his professional career as an assistant professor in the Purdue University Agricultural Engineering Department in July 1994. Thus continues a lifelong association with agricultural machines and the people who make them work for all of us.

Dan Ess