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Effects of Soil Cultivation Techniques on
Rooting of Kentucky Bluegrass Sod

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Paul E. Rieke
Major professor

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EFFECTS OF SOIL CULTIVATION TECHNIQUES ON ROOTING OF KENTUCKY BLUEGRASS SOD

by

Douglas Kwai-keng Lee

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ABSTRACT

EFFECTS OF SOIL CULTIVATION TECHNIQUES ON ROOTING OF KENTUCKY BLUEGRASS SOD

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The potential benefits in using vertically operating tine cultivation as a means of soil preparation for sodding was evaluated. Several benefits of cultivation techniques were evident on a short term basis (1-2 months after treatment). Cultivation with solid tines was most beneficial to sod rooting when done under low soil moisture conditions. Hollow tine cultivation was more conducive to sod rooting when done under the low and medium moisture levels, while rototill cultivation was more effective under the higher moisture regime. All cultivation treatments were effective in reducing bulk density and increasing pore space of the sandy loam soil studied under the lower moisture regimes. Rototill cultivation was effective in increasing macropores and reducing bulk density under medium and higher moisture conditions. Soil strength was effectively reduced by cultivation under all moisture conditions. Over the longer term (9-10 months) the improvement in soil properties was lost in that there was no measurable difference between cultivated plots and the check. However, there was still an advantage from cultivation in sod rooting.

to my family,
especially to my loving wife, Sharon,
for her love, support and patience

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INTRODUCTION

In the United States the total area devoted to turfgrasses is estimated to be 10 to 12 million hectares. The expenditures of turfgrass industry are considered to be more than $25 billion per year with an estimated half a million people making a living directly from the care and maintenance of turf. Of the total area under turfgrass, 81 % (8.1 to 9.7 million hectares) are home lawns. The sale of lawn care items is estimated at $4 billion a year, nearly a third of the total amount spent on gardening (Roberts, 1988).

A significant problem on many home lawns is soil compaction. Compaction occurs as a result of construction practices using heavy machinery and can also be caused by traffic. Soil compaction reduces pore space, increases soil strength and bulk density, reduces infiltration, percolation and aeration thus adversely affecting plant growth and rooting. Turf growing on compacted soil will not root as deeply and will be more subject to stresses.

Frequently, lawn turfs are established on compacted subsoils. It is important to prepare the soil as carefully as possible before turf establishment for long term high quality, stress tolerant turf.

The most effective way to alleviate soil compaction is cultivation. A commonly used cultivation technique for preparing soil for turf establishment is rototilling. Rototilling is effective in loosening the soil but is costly, labor intensive and requires further soil leveling and settling. An alternative to rototilling, as a means of soil preparation, could be cultivation with traditional core cultivation equipment. However, little is know about the impact of such cultivation practices on loosening bare soil and ultimately, on turfgrass sod rooting.

LITERATURE REVIEW

Soil compaction can be defined as pressing soil particles together into a more dense soil mass. Compaction alters soil physical properties such as air porosity, bulk density and soil strength which in turn affect movement of water and gas exchange. Soil compaction is common on heavily used turfgrass areas but can also occur prior to turfgrass establishment by heavy earth moving equipment used in construction especially when soils are too wet. Compaction is not only caused by human or vehicular traffic but also by falling raindrops or droplets from irrigation on bare soil (Beard, 1973).

Compaction limits root growth. The three most frequently published explanations for poor root growth in compacted soil are mechanical impedance (Barley and Greacen, 1969), reduced soil pores and aeration, and increased bulk density and soil strength (Boufford and Carrow, 1980; Carrow, 1980; Cordukes, 1969).

MECHANICAL IMPEDANCE

Gill and Miller (1956) investigated effects of mechanical impedance and oxygen supply to roots as factors responsible for poor growth of corn (Zea mays L.) roots in some compacted soils. They designed a root growth pressure apparatus safe for operation up to 10 atmospheres. They found that a reduction in oxygen concentration reduced the rate of growth of confined and unconfined roots. Growth was adversely affected by merely reducing by half the oxygen content of soil air. The rate of growth fell to zero at relatively small levels of impedance if oxygen content was low. Barley and Greacen (1967) also reported that mechanical impedance has widespread influence on root penetration and growth.

Tackett and Pearson (1964) found that the depth of root penetration decreased as bulk density increased over the entire range studied. Oxygen content below about 10 % in soil air sharply reduced root penetration. They also found that mechanical impedance was more detrimental than oxygen for root growth in subsoils at bulk densities above 1.5 g cc^{-1}. At lower bulk densities, root growth was depressed at oxygen levels below 10 % and there was a strong interaction between oxygen and bulk density. Aubertin and Kardos (1965) showed that the best plant and root growth occurred when the aerating gas contained 10 % oxygen.

Changing the oxygen level to higher or lower percentages resulted in decreased plant and root growth.

Root penetration and proliferation in subsoil can be influenced by nutrient availability, toxicities, mechanical restriction, level of aeration, water availability and other factors (Boynton and Compton, 1943; Chang and Loomis, 1945; Hopkins et al., 1956; Leonard, 1945; Vlamis and Davis, 1944).

POROSITY and OXYGEN DIFFUSION RATE (O.D.R)

Soil compaction reduced both total air capacity of a soil at field capacity and the air transmission rate of a soil (Vomocil and Flocker, 1961). Aeration porosity at -100 kPa was reduced from 25 (uncompacted) to 21 and 17 % for moderate and heavy compaction treatments, respectively (O'Neal and Carrow, 1983). At higher water potentials, lower porosity under no-cultivation may restrict gaseous exchange and create conditions unfavorable for germination and seedling development. Air filled porosity of surface soil under no-cultivation was lower than cultivated soil at all potentials measured (Gantzer and Blake, 1978).

Stolzy et al. (1961) investigated oxygen diffusion rate and found that oxygen treatment appeared to influence root vigor. Roots with 21 % oxygen treatments had a thick network of roots going deep in the soil while the 0.7 % oxygen treatment had roots which were only barely visible. They found six of the eight treatments had root growth stopped in a diffusion rate range of 18 to 23 x 10^{-8} g cm^{-2} min^{-1}. They suggested a value of approximately 20 x 10^{-8} g cm^{-2} min^{-1} as the minimum threshold for oxygen diffusion rate for root growth. This value agreed with the finding of Betrand and Kohnke (1957) on corn roots. Lemon and Erickson (1952) however, found that the threshold for oxygen diffusion rate (O.D.R.) value varied in tomatoes (*Lecopersicum esculentum*); 30 to 40 x 10^{-8} g cm^{-2} min^{-1}. Wiersma and Mortland (1953) also found 20 to 30 x 10^{-8} g cm^{-2} min^{-1} was critical in the growth of sugar beets (*Beta vulgaris*). Hanks and Thorp (1956) found that for seedling emergence of wheat (*Triticum aestivum* L.) , a value of 75 to 100 x 10^{-8} g cm^{-2} min^{-1} was ideal.

O'Neal and Carrow (1983) reported that compaction reduced O.D.R. values below 20 x 10^{-8} g cm^{-2} min^{-1} which were found 53 hours after irrigation under a heavy compaction treatment. In contrast, for non-compacted pots, O.D.R. values were near acceptance levels within five hours. Oxygen diffusion rate measurements correlated well with aeration porosity and low O.D.R. values were found to restrict root growth (Waddington and Baker, 1965; Wijk, 1980; Agnew and Carrow, 1985). Allmaras et al. (1967) showed that total porosity increases due to plowing were significantly affected by the moisture content at tillage time. Porosity was greatest at low moisture content, decreased approximately linearly as soil moisture increased to the lower plastic limit (LPL).

For proper plant root growth, adequate soil aeration is essential. Oxygen may become limiting and carbon dioxide may become excessive without soil aeration (Cannell, 1977; Grable, 1966; Meek and Stolzy, 1978). Meek and Stolzy (1978) also found that restriction of soil aeration for 24 hours can reduce root growth, while longer periods may result in root cell death.

BULK DENSITY and SOIL STRENGTH

Taylor and Burnett (1963) investigated the influence of soil strength on root growth habits of cotton (Gossypium hirsutum L.). They found that a few weeks after seed germination most of the seedling plants died in pots with no-cultivation, compacted soil while plants planted on cultivated, compacted pots survived.

Barley (1963) found that when air and water were not limiting, roots were unable to elongate in a fine grained soil where shear strength exceeded 0.3 Kg cm^{-2} and there was a continous decrease in the rate of root elongation as the strength increased. Penetration and growth of roots were controlled chiefly by the soil strength (Barley et al., 1965; Lutz, 1952).

Laboratory investigations indicated soil strength, not soil bulk density controlled penetration of cotton taproots through cores of Amarillo fine sandy loam soil at -20 to -60 kPa soil moisture tension (Taylor and Gardner, 1963).

Taylor et al. (1965) investigated four types of soil and found that the soil strength increased as soil bulk density increased. However, when the four soils were compared at a specific soil bulk density, there were large differences among the resultant soil strengths. At -33 kPa water potential, and a bulk density of 1.55 g cc^{-1}, the soil strength of each type of soil varied from 19 to 6 bars. Based on other data on this experiment they concluded that root penetration percentage was reduced drastically as soil strength increased to 25 bars and no taproots penetrated through cores with strengths greater than 25 bars, regardless of the soil material.

EFFECTS on ROOTS

Soil compaction causes a marked reduction in the weight of roots. On non-compacted plots, 70 % of the root weights were found in the upper 15 cm of soil while in a cultivated, compacted soil, root percentage in the upper 15 cm increased to 89 % (Taylor and Burnett, 1963; Taylor and Gardner, 1963). Other studies also showed that turf root growth declined with compaction (Cordukes, 1969; Letey et al., 1966; Thurman and Pokorny, 1969). Valoras et al. (1966) found that compaction reduced root growth in bermudagrass (Cynodon dactylon L.). Letey et al. (1966) found that compacted soil resulted in areas with few young roots and root permeability decreased due to root maturity.

Sills and Carrow (1983) reported that the most detrimental effects of compaction were on root weight and distribution at a higher N rate. Increasing rate of N application to encourage more growth did not increase rooting. Compaction reduced perennial ryegrass (Lolium perenne L.) root weights 30.6 % in all soil depths. Compaction applied in conjuction with the lower N rate caused a 13.3 % reduction in total rooting but at the high N rate a 44.6 % decrease occurred. In a field study on tall fescue (Festuca arundinacea Schreb.), compaction plus N reduced total root growth by 48 % compared to the uncompacted turf plus N (Sills and Carrow, 1982).

Agnew and Carrow (1985) investigated root response to soil compaction and moisture stress preconditioning on Kentucky bluegrass (Poa pratensis L.) and found that long-term compaction (equivalent to 720 J energy over 99-day period) increased root weights in the upper 5 cm and decreased root weights in the lower 10 to 20 cm profile. Short-term compaction (9-day period) decreased root weights only at the 15 to 20 cm depth.

DeWitt (1978) reported that branching of roots and surface adventitious root formation were induced by low soil aeration. He also noted that if oxygen stress was longer than 24 hours, the roots generally became damaged but viability could be restored if oxygen stress was less than 24 hours. Watson (1950) observed that moisture level influenced turf quality more than did soil compaction.

Wilkinson and Duff (1972) compared rooting of annual bluegrass (Poa annua L.), creeping bentgrass (Agrostis palustris Huds.) and Kentucky bluegrass at different bulk densities under growth chamber conditions and found no difference among species, although root growth significantly increased as soil density increased from 1.1 to 1.4 g cc^{-1}. They attributed the increase in root growth to increased water availability at higher densities and the soil being sandy loam in which soil oxygen is usually less limiting. Moreover, root growth under relatively low bulk density is also not limiting.

Veihmeyer and Hendrickson (1948) showed the critical density needed to inhibit sunflower (Helianthus annus L.) root growth varied with texture. They found no roots penetrated soil of a 1.9 g cc^{-1} bulk density. Taylor et al. (1966), Cockroft et al. (1969) and Blanchar et al. (1978) showed that root growth ended when soil strength reached 2.0 - 2.5 MPa. Wiersum (1957) noted that roots can enter pore sizes of smaller diameter than the young root itself only if rigidity of the pore structure was weak enough to allow the root to cause soil displacement.

CULTIVATION

Turgeon (1980) described cultivation as mechanical methods of selective tillage that modify soil, and possibly other characteristics of a turf. Beard (1973) described cultivation as a mechanical method of improving the exchange of air and water between the atmosphere and soil without causing disruption of the turf surface.

Cultivation is one practice effective in alleviating soil compaction whether on turfed areas, agriculture soils or bare ground. A number of cultivation methods and equipment have been developed for turf areas over the years (Mendenhall, 1949). The primary methods are coring, grooving, slicing, forking and spiking. In agriculture, plowing, disking, chiseling and harrowing are common methods of cultivation.

Tillage altered both soil physical and chemical properties, which in turn altered the environment for root growth and improved plant growth, nutrient uptake and yield (Anderson, 1987). In tilled and untilled soil, soil strength appeared to be the main soil physical factor controlling root growth. Ehlers et al. (1982) found that in tilled soil, mechanically produced planes of weakness seemed to influence penetration resistance, and root growth depended on their number and extension per unit volume of soil. In rigid soil matrix of an untilled soil, roots followed pathways of low or practically no resistance, such as channels created by earthworms or smaller pores created by the roots of preceeding crops.

When soil was compacted soil strength increased and when compacted soil was tilled, the strength decreased (Taylor and Burnett, 1963). Tillage destroyed coarse soil aggregates and traffic following tillage quickly recompacted the soil (Sommer, 1988).

Eggens and Carey (1988) indicated that high intensity site preparations resulted in significantly less stress and more rapid recovery of new sod.

Core cultivation has been used extensively in turf areas, particularly on golf course turfs. One type of core cultivation equipment uses hollow tines which are operated vertically. Soil cores are removed from established turf to alleviate soil compaction problems. However, destruction of soil structure may occur due to localized soil compaction (Engel, 1970). Petrovic (1979) set up a laboratory study to examine soil density changes caused by penetration of hollow tines on laboratory prepared soil cores. He found large bulk density increases in the soil surrounding the coring hole. He suggested this might lead to development of a hardpan below the cultivation zone.

Murphy (1986) studied effects of cultivation with hollow and solid tines on soil structure and turfgrass root growth. He found that while cultivation increased large soil pores (at water potential of -1 kPa), a corresponding decrease in micropores (between water potential of -10 to -100 kPa) occurred on non-compacted soil. Solid tine cultivation increased micropores compared to hollow tine cultivation. He also found that solid tines were more effective in loosening the surface soil initially, but this effect reversed by the end of the study. Murphy and Rieke (1986) also showed that cultivation reduced soil density by slightly increasing total porosity.

Goss and Brauen (1985) reported that solid tine cultivation was effective in softening compacted soil. It increased infiltration rates and rooting improved. Carrow (1988) showed that cultivation with hollow tine coring, solid tine coring (shattercoring), Aer way slicer and Ryan slicer were effective in alleviating compaction. Murphy and Rieke (1989) indicated that cultivation using the Verti-Drain aerifier was the most effective of several aerifiers in alleviating subsurface compaction due to its ability to cultivate deeply and the close spacing of the tines. They concluded that cultivators with widely spaced tines may require several passes to sufficiently breakup the compacted surface zone and ideally, coring holes should be spaced no greater than 7.6 cm apart on highly compacted turf sites.

Rototilling the soil is one common method of cultivation used in preparing the soil for establishing turfgrass. Increasing interest has developed recently in using Vertically Operating Tine (VOT) cultivation as an alternative to rototilling. The main reason for this growing interest is that rototilling is costly, labor intensive and requires further soil leveling and settling compared to VOT

cultivation. However, the effects of cultivation with VOT equipment as a soil preparation method has not been documented.

EFFECTS of WETTING AGENTS and SOIL AMENDMENTS on SOD ROOTING

Some interest has developed recently in using soil amendments (wetting agents, soil conditioners and seaweed biological agent extracts) as a treatment to enhance rooting of turfs and improve soil physical properties.

Schmidt and Goatley (1987) found that seaweed extract, BA (6-Benzylaminopurine), and Aqua-Gro enhanced rooting when sod was cut and transported 7 to 10 days after treatment and measured via vertical pull 4 weeks later. Middleton (1987) suggested that sea plants, liquified sea plant extract and granulated seaweed meal strengthened root systems and stimulated microbiological activity in the soil. Moore (1974) proposed that wetting agents improved soil wettability, infiltration, and drainage, reduced bulk density of compacted loam soil and reduced evaporation loss. Further studies to evaluate the effects of soil amendments as a method of alleviating soil compaction are needed.

The objectives of this research, therefore, were to determine the effects of VOT cultivation and soil amendments on alleviating soil compaction and preparing the soil for turf establishment by sodding.

MATERIALS AND METHODS

A total of five studies were conducted to investigate the effects of the various soil treatments on the rooting of newly sodded turf.

The technique used in the measurement of root development, initiated by King and Beard (1969), involved placing a piece of sod cut to fit into a rooting box. The wooden rooting box had dimensions of 30.5 cm x 30.5 cm I.D., with a fiber glass screen (18 x 16 mesh) attached to the base. A wire hook was placed at each of the four corners of the rooting box. The sod in the rooting box was placed on the treated plot and allowed to grow. Kentucky bluegrass (Poa pratensis L.) sod was used for all the studies. The sod was planted to a mix of 50 % Bristol and 50 % Victa cultivars and was grown on muck soil.

Additional strips of turf were sodded around boxes for a uniform microenvironment. The sod rooting boxes were aligned in rows to accommodate mowing (walk behind rotary mower) practices. The first mowing was done approximately two and a half weeks after sodding. Subsequently, the turfgrass was mowed

weekly at a mowing height of 7.5 cm. In studies I, II, IV and V, the plots were irrigated daily for seven days after sodding with a sprinkler system. However, in Study III, the plots were watered by hand. After the initial 7-day period, the plots were irrigated only to prevent wilt. All the plots were irrigated the day before each extraction date, so as to maintain uniform soil moisture content during the lifting of the sod rooting boxes. During the course of the study no pesticides were applied.

At appropriate times selected boxes were lifted to evaluate the degree of rooting which had occurred. The rooting box was lifted by connecting a cable onto each wire hook. The cables in turn were connected to a load cell that was attached to a hydraulic lifting device, as shown in Figure 1. The extractor was centered over the rooting box so that the lifting force was in a vertical direction. The hydraulic system was considered essential because it provided a uniformly increasing force that could be applied to lift the rooting boxes. The force required to lift the rooting box was recorded. This force included the following: the weight of the rooting box, the weight of sod, weight of soil lifted with the rooting box and the true lifting force. The true lifting force was calculated by subtracting the weights of the rooting box, sod and soil from the extraction force. The soil was then cut loose from the rooting box with a knife and returned to the original spot and resodded. Previous studies (King and Beard, 1969; Schmidt et al. 1986) have

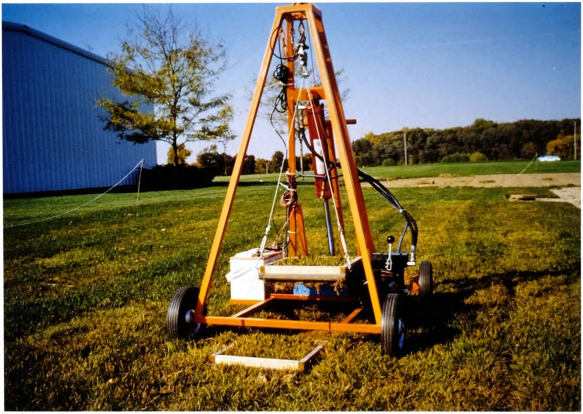

Figure 1. Hydraulic Lifting Device

shown that there was a direct correlation between the lifting force and root development.

Cultivation treatments in Studies I, II, and V were executed on the dry soil (soil moisture content between 2-4 % by weight). The data were subjected to analysis of variance. When a significant treatment effects occurred the Duncan's Multiple Range Test was used to determine the significance of the treatment means.

STUDY I - Effect of Cultivation on Sod Rooting.

Treatments were initiated August 11, 1987 and plots sodded August 12, 1987 at the Michigan State University Robert Hancock Turfgrass Research Center, East Lansing. The soil was a sandy loam subsoil with a particle size analysis consisting of 68.9 % sand, 18.7 % silt, and 12.4 % clay, with 1.4 % O.M., determined by loss on ignition. The five treatments were no cultivation (CHK), compacted (COM), hollow tine coring (HTC), solid tine coring (STC), and rototilling (ROT). A TORO vertical operating aerifier was used to execute the coring cultivation using 1.27 cm solid and hollow tines. Compaction treatments, with a static pressure of 0.52 Kg cm^{-2}, were applied using a Ryan's vibrating roller averaging five passes to ensure uniformity. A walk behind rototiller was used to execute the rototilling treatment averaging two passes. At the time of cultivation, the soil had a moisture content of two to four percent

by weight. The depth of all the cultivation treatments was approximately 7.6 cm.

The size of each treatment plot was 91 cm x 91 cm. The plots were arranged in a complete randomized block design with four replications and three extraction periods for a total of 60 experimental plots. Each plot contained two rooting boxes (2 subsamples) and were placed 10 cm apart. The plots were fertilized after sodding with an 18-4-10 fertilizer at a rate of 24.4 Kg N ha^{-1}. The second and third fertilizer applications were September 11, 1987 and May 15, 1988, respectively.

The first set of rooting boxes were lifted September 9, 1987, the second October 30, 1987, and the third June 21, 1988. In all cases sod lifting was done when soil moisture was in the range of 10-11 % by weight. Roots grown on this soil did not break at the sod-soil interface when the rooting box was lifted. The lifting force, weight of soil, weight of sod and rooting box, were recorded.

STUDY II - Effects of Wetting Agents and Soil Amendments on Sod Rooting.

Treatments were initiated and plots were sodded September 9, 1987. The soil and study site were similar to Study I. Before the plots were treated, they were compacted with five passes using the vibrating roller to ensure uniformity of soil condition. The 16

treatments were Control(CHK), Aqua-Gro at a rate of 336 Kg ha^{-1} (AQUA 1), Aqua-Gro at a rate of 674 Kg ha^{-1} (AQUA 2), Naiad at a rate of 3.1 Kg ha^{-1} (NAIA 1), Naiad at a rate of 6.2 Kg ha^{-1} (NAIA 2), TurfTech at a rate of 0.6 Kg ha^{-1} (TURF 1), Panasea at a rate of 6.1 Kg ha^{-1} (PANA 1), Panasea at a rate of 12.2 Kg ha^{-1} (PANA 2), Biocontrol at a rate of 6.1 Kg ha^{-1} (BIOC 1), Biocontrol at a rate of 12.2 Kg ha^{-1} (BIOC 2), Biocontrol at a rate of 24.4 Kg ha^{-1} (BIOC 3), Agrilyte at a rate of 343 Kg ha^{-1} (AGRI 1), Agrilyte at a rate of 686 Kg ha^{-1} (AGRI 2), Regenerate at a rate of 134 Kg ha^{-1} (REGE 1), Regenerate at a rate of 269 Kg ha^{-1} (REGE 2), and Regenerate at a rate of 538 Kg ha^{-1} (REGE 3).

The plots, each measuring 91 cm x 91 cm, were arranged in randomized complete block design with four replications. Each plot contained one rooting box.

Treatments AQUA 1, AQUA 2, NAIA 1, NAIA 2, TURF 1, PANA 1, PANA 2, BIOC 1, BIOC 2, BIOC 3 and check received urea at a rate of 48.8 Kg N ha^{-1}. Treatments AGRI 1 and REGE 1, with inherent N content equivalent to 12.2 Kg ha^{-1}, received urea at a rate of 36.6 Kg N ha^{-1}. Treatments AGRI 2 and REGE 2, with inherent N content equivalent of 24.4 Kg ha^{-1}, received urea at a rate of 24.4 Kg N ha^{-1}. Treatment REGE 3, which has an inherent N content equivalent to 48.8 Kg ha^{-1}, did not receive additional N. Agrilyte, Regenerate and Aqua-Gro were applied as granules. Naiad, Panasea and Biocontrol were liquids while TurfTech was a powder;

each of these were mixed with 150 ml. water before being sprayed onto the plots. The rooting boxes were lifted October 15, 1987.

STUDY III - Effects of Cultivation and Soil Amendments on Sod Rooting.

Treatments were initiated and plots sodded September 21, 1987. The site of the study was located beside Baker Wood, Michigan State University, on the Soil Science Research Farm. The soil was a sandy clay loam subsoil with a particle size analysis consisting of 54.9 % sand, 22.7 % silt, and 22.4 % clay with 1.0 % O.M. It had a bulk density range between 1.97 and 2.13, consequently no compaction treatments were applied. All the cultivation treatments were similar to Study I and six treatments were similar to some selected treatments of Study II. The 10 treatments were Control (CHK), HTC, STC, ROT, TURF 1, BIOC 2, BIOC.3, AQUA 2, REGE 3 and AGRI 2 (see page 16).

All plots received urea at a rate of 24.4 Kg N ha^{-1} except for treatments REGE 2 AND AGRI 2, which had an inherent N content at an equivalent amount. The fertilizer was applied first followed by the treatments. The cultivation treatments were executed similarly to Study I.

The plots, each measured at 91 cm x 91 cm, were arranged in complete randomized block design with four replications and one extraction for a total of 40 experimental plots. Each plot contained

two rooting boxes (2 subsamples) and were spaced 10 cm apart. The rooting boxes were lifted June 5, 1988.

STUDY IV - Effects of Cultivation on Sod Rooting, Soil Porosity, Bulk Density and Soil Strength.

Treatments were initiated July 14, 1988, located near the site of Study I. The cultivation treatments used in Study I were performed at three different moisture regimes, 2 to 4 % (M1), 4 to 8 % (M2) and 8 to 12 % (M3) soil moisture by weight, at the time of cultivation.

All the plots were compacted with five passes using the vibrating roller, to ensure uniformity of soil condition. The three moisture regimes were achieved by wetting the respective plots with water using a watering can. There was no wetting on M1 plots. Whatever amount of water was applied to M2 plots, M3 plots received twice as much. The soil had a slow infiltration and percolation rate and in order to prevent surface runoff, small increments of water were added at regular intervals to achieve the desired moisture regimes. Due to the hot summer days, the plots had to be covered frequently with a tarpaulin to minimize moisture loss. The wetting procedure took two days to wet the soil to a depth of at least 7.6 cm. Soil samples were taken to a depth of 7.6 cm. to determine the moisture range of each moisture regime; with 4 subsamples per moisture regime per replication. Once the

soil moisture ranges were achieved, the cultivation treatments were executed similarly to Study I. Soil moisture levels for the three moisture regimes determined on samples taken previous to cultivation treatments showed the moisture content of the soils for each regime were as follows: M1 moisture levels ranged from 2.5 to 4.0 %, averaging 3.5 %; M2 ranged from 4.4 to 8.0 %, averaging 6.5 %, and M3 ranged from 8.2 to 11.3 %, averaging 10.0 %. The four treatments were No cultivation (CHK), HTC, STC, and ROT.

The plots were arranged in split plot design, in which the soil moisture regimes were the main plot and the cultivation treatments were the subplots, with four replications and one extraction for a total of 48 experimental plots. Each plot contained one rooting box. The size of each treatment plot was 152 cm x 91 cm, large enough to accommodate core sampling and penetrometer readings.

After all the cultivations had been executed the plots were then irrigated to saturate the soil in order to speed up the resettling process. This procedure was repeated weekly for three weeks. Three soil core samples were taken from each plot August 2, 1988, using a 7.6 cm I.D. x 7.6 cm depth aluminum sampling cylinder for laboratory determinations of air porosity and bulk density. Air porosity determinations were made at -1, -6, -10, -100 kPa and oven dry (105°C) moisture potentials.

A depth monitoring penetrometer (Davidson, 1965) was used to take four readings per plot August 3, 1988. The soil moisture was between 8 to 10 % by weight.

After the soil core samples and the first set of penetrometer readings were taken, the plots were sodded August 4, 1988; each plot contained one rooting box. The plots were fertilized after sodding with an 18-4-10 fertilizer at a rate of 24.4 Kg N ha^{-1}. Repeat fertilizer applications were made September 11, 1988 and May 18, 1989, respectively. The rooting boxes were lifted June 9, 1989 and the lifting force, weight of soil, and weight of sod and rooting box, were recorded.

At the end of the study, another set of soil core samples were taken June 10, 1989; removing the sod and the thatch first before taking the core samples. The second set of penetrometer readings was taken June 16, 1989 but at the soil moisture of 14.7 % by weight due to wet weather conditions.

STUDY V - Effect of Cultivation on Sod Rooting.

This study was a repeat of Study I. Treatments were initiated August 1, and sod was laid August 2, 1988. The plots were fertilized at similar times and rates as Study IV. The rooting boxes were lifted August 31, 1988, September 30, 1988, and June 8, 1989.

RESULTS AND DISCUSSION

STUDY I and STUDY V - Effects of Cultivation on Sod Rooting.

The force required to lift the rooting boxes is shown in Table 1 (Study I) and Table 2 (Study V). The results in Table 1 show that on the first extraction date (one month after sodding), the solid tine coring (STC) and rototilling (ROT) treatments required more force to lift the rooting boxes as compared to the non-cultivated (Check and Compacted) treatments. Previous studies (King and Beard, 1969; Schmidt et. al., 1986) have shown that there was a direct correlation between lifting force and root development. Therefore, it is assumed STC and ROT plots had better root development in this study. The hollow tine coring (HTC) treatment had a somewhat lower lifting force as compared to STC and ROT. This could have been due to soil cores which had been left on the soil surface before placing the rooting boxes on the plots. This may have resulted in small air pockets between the soil surface and the screen on the bottom of the rooting box which could slow the rate of new root establishment into the soil. However, in an observation

Table 1. Effects of cultivation on force required to lift rooting boxes. STUDY I. Treatments initiated 8/11/87.

Treatments	Mean Lifting Force*		
	9/9/87	10/30/87	6/21/88
	-------------	Kg	-------------
Check	20.6 b**	38.6 c	79.9 b
Compacted	20.3 b	38.0 c	64.6 c
Hollow tine coring	27.9 ab	49.7 b	90.5 ab
Solid tine coring	35.1 a	56.9 ab	97.5 a
Rototilling	34.0 a	60.4 a	84.7 b

* Extraction of rooting box at 10 to 11 % soil moisture by weight.

** Any two means followed by the same letter are not significantly different at p=.05 by Duncan's Multiple Range Test.

Table 2. Effects of cultivation on force required to lift rooting boxes. STUDY V. Treatments initiated 8/1/88.

Treatments	Mean Lifting Force*		
	8/31/88	9/30/88	6/8/89
	------------	Kg	------------
Check	27.4 b**	41.5 b	67.9 c
Compacted	26.5 b	33.9 c	66.2 c
Hollow tine coring	30.7 ab	48.3 a	79.6 ab
Solid tine coring	33.0 ab	51.0 a	84.8 a
Rototilling	35.2 a	52.6 a	73.5 bc

* Extraction of rooting box at 10 to 11 % soil moisture by weight.
** Any two means followed by the same letter are not significantlyl different at p=.05 by Ducan's Multiple Range Test.

plot adjacent to this study, air pockets dug by hand tool were deliberately created between the screen on the rooting box and the soil surface to observe if this would affect sod rooting. No reduction in root growth was observed.

In Study V (repeat of Study I), the lifting weights one month after sodding on HTC, STC and non-cultivated plots (Check and Compacted) were not statistically significantly different although the force required to lift the rooting boxes was higher on STC and HTC plots (Table 2). This could be due to the hot summer weather in 1988, which may have affected the growth rate of the turfgrass and rooting one month after sodding.

On the second extraction date (two months after sodding), a greater separation among means between the cultivated and non-cultivated treatment plots occurred in both studies. Based on the data, it is assumed that the roots in the cultivated plots appeared to be significantly better developed than in the non-cultivated plots. The lifting force on HTC plots, which showed no significant difference when compared to the non-cultivated plots in the first extraction, increased by 21.8 Kg over the first extraction (Table 1), while the check plot increased only by 18 Kg. The lifting force of STC and ROT increased by 21.8 and 26.4 Kg, respectively. This pattern appeared to be consistent in both studies as shown in Tables 1 and 2. In Study V, a greater separation among means between the non-cultivated treatments also began to occur. The

results showed that CHK plots had better root development than COM (compacted) plots.

On the third extraction date (6/21/88 in Study I), results showed that COM plots had the lowest lifting force, and therefore the least developed root system compared to the other treatments. Thus soil compaction impeded rooting. However, in Study V (6/8/89 in Table 2), the lifting force of the the compacted plot was lower than the check but there was no significant difference.

Solid tine cultivation plots, on the other hand, had the highest lifting force although there was no significant difference between STC and HTC treatments. This could be attributed to the shattering effect of the tines created by the high energy impact vertical aerifier.

Among the cultivated plots, ROT cultivation had the lowest lifting force at the end of the study, whereas on the second extraction date, it required the most force. In Study I, the lifting force on ROT plots, from 10/30/87 to 6/21/88 (between second and third extraction dates), increased by 24 Kg, while each HTC and STC plots increased by 41 Kg. This pattern also repeated in Study V. It is assumed that this decline in root growth in the rototilled plots may be due to the instability of the fine soil aggregates created by the rototilling effect which appeared to recompact easily. Taylor (1986) showed similar effects. Other studies have shown that rototilling can destroy soil structure (Sommer, 1988). This could be

harmful to the long term stability of soil structure and could lead to poorer rooting and susceptiblity of the turf to stresses.

These data suggested vertically operated cultivation techniques can offer an effective alternative to rototilling. Cultivation clearly enhanced rooting while compacted soil adversely affected root development.

The weight of soil lifted with the sod rooting boxes is shown in Table 3 (Study I) and Table 4 (Study V). The weight of soil lifted was quite well correlated with the force required to lift the sod rooting boxes (Tables 1 and 2). The soil weights of the cultivated plots (HTC, STC and ROT) were generally greater than the non-cultivated plots (CHK and COM) 2 months and 10 months after sodding. In Study V, however, the data from the first extraction (8/31/88) and the third extraction (6/8/89) differed slightly from this pattern. The warm weather of August, 1988 may have caused a slower growth rate, consequently affecting the first extraction results. Clearly soil weights for the first extraction date were lower in 1988 than in 1987. The third extraction date results differed from Study V possibly due to 1) wetter soil condition at the time of extraction (14.7 % moisture by weight compared to 10 to 11 % for the other extractions or 2) the hot dry weather of May and June, 1988 which could have had a negative effect on rooting for the 6/21/88 extraction.

Table 3. Weight of soil lifted with the sod rooting boxes for the three extraction dates. STUDY I. Treatments initiated 8/11/87.

Treatments	Mean Soil Weight **		
	9/9/87	10/30/87	6/21/88
	Kg		
Check	1.6 b*	2.2 c	8.5 c
Compacted	1.7 b	2.0 c	7.4 c
Hollow tine coring	2.5 ab	4.1 b	13.9 a
Solid tine coring	3.5 a	5.8 a	13.2 a
Rototilling	3.4 a	6.3 a	11.0 b

* Any two means with the same lettler are not significantly different at p=.05 by Duncan's Multiple Range Test

** Extraction of rooting box at 10 to 11 % soil moisture by weight

Table 4. Weight of soil lifted with the sod rooting boxes for the three extraction dates. STUDY V. Treatments initiated 8/1/88.

Treatments	Mean Soil Weight		
	8/31/88**	9/30/88**	6/8/89*
	Kg		
Check	0.8 ab***	2.2 b	15.1 a
Compacted	0.5 b	2.1 b	12.1 b
Hollow tine coring	1.5 ab	7.3 a	16.8 a
Solid tine coring	1.9 a	6.8 a	15.2 a
Rototilling	1.7 ab	5.9 a	17.0 a

* Extraction of rooting box at 14.7 % soil moisture by weight

** Extraction of rooting box at 10 to 11 % soil moisture by weight

*** Any two means with the same lettler are not significantly different at p=.05 by Duncan's Multiple Range Test

STUDY II - Effects of Wetting Agents and Soil Amendments on Sod Rooting.

The force required to lift the rooting boxes is presented in Table 5. The data showed no significant difference among the treatments. Application of wetting agents (Aqua-Gro and Naiad), and soil amendments (Agrilyte, Regenerate, Biocontrol and TurfTech) on bare ground without cultivation as a site preparation technique for sodding did not improve root penetration into the soil. Root penetration into compacted soil appeared to be inhibited by the mechanical resistance of the soil (Aubertin and Kardos, 1965; Tackett and Pearson, 1964).

These results indicate that relief of soil compaction or stimulation of root growth did not occur over this 5-week study. The compaction problem must be alleviated by loosening the soil before a good root system can be developed. It is recognized that more time may be needed to permit significant changes in soil properties as a result of treatments. These data suggest there were no short term benefits from these treatments under the conditions of this study but does not address any potential long-term benefits.

Table 5. Effects of soil amendments on force required to lift rooting boxes. STUDY II. Treatments initiated 9/9/87 and Extracted 10/15/87.

Treatments	Rate per hectare	Lifting Force
	----------- Kg**	----------
Aqua-Gro	336.1	39.5 NS*
Aqua-Gro	674.2	42.2 NS
Naiad	3.1	43.2 NS
Naiad	6.1	43.2 NS
Turftech	0.6	38.7 NS
Panasea	6.1	40.2 NS
Panasea	12.2	37.0 NS
Biocontrol	6.1	35.7 NS
Biocontrol	12.2	38.4 NS
Biocontrol	24.4	41.4 NS
Agrilyte	343.1	39.8 NS
Agrilyte	686.2	39.5 NS
Regenerate	134.4	44.7 NS
Regenerate	268.9	39.1 NS
Regenerate	537.8	38.8 NS
Control	-	35.2 NS

* NS Not significantly different at p=.1 by Duncan's Multiple Range Test.

** Extraction of rooting box at 8 % soil moisture by weight.

STUDY III - Effects of Cultivation and Soil Amendments on Sod Rooting.

The forces required to lift the rooting boxes and the weight of soil lifted are presented in Table 6. The cultivation treatments utilized in Studies I & V and selected treatments from Study II, were chosen for this study located on this compacted sandy clay loam soil.

There was little significant difference among treatments in this study. All lifting weights were higher than observed in Studies I and V. This may have been due to the fact that at 10% moisture the soil strength of the sandy clay loam would be higher than for the sandy loam at the same moisture level.

The two parameters that were different between this study and Studies I and V were soil texture and bulk density. This soil had a sandy clay loam texture with 10 % more clay and a bulk density ranging from 1.97 to 2.13 g cc^{-1} whereas in Studies I and V the soil had a sandy loam texture with a bulk density of 1.8 g cc^{-1}.

Nevertheless, the weight of soil lifted with the rooting box showed some significant differences among the cultivated plots, particularly for hollow and solid tine cultivation, compared to the control. In contrast the soil weights were lower for this study than at the conclusion of Studies I and V.

The data also showed that soil treated with soil amendments did not promote deeper root development or alleviate soil

Table 6. Treatment effects on force required to lift rooting boxes and weight of soil lifted with rooting boxes. STUDY III. Treatments initiated 9/21/87 and extracted 6/5/88.

Treatments	Rates /hectare	Lifting Force	Soil Weight
	---------------- Kg**	-------------	
Control	-	111.4 abc	6.5 bc*
Hollow tine coring	-	116.2 ab	9.9 a
Solid tine coring	-	115.7 ab	9.3 a
Rototilling	-	113.9 ab	8.4 ab
Turftech	0.6	115.1 ab	5.7 c
Biocontrol 2	12.2	118.1 a	6.3 bc
Biocontrol 3	24.4	118.9 a	5.4 c
Aquagro 2	674.2	104.6 bc	5.0 c
Regenerate 1	134.4	108.1 abc	6.0 bc
Agrilyte 2	686.2	100.5 c	5.5 c

* Any two means with the same letter are not significantly different at p=.05 by Duncan's Multiple Range Test

** Extraction of rooting box at 10 % soil moisture by weight

compaction under the conditions of this study. This was consistent with observations from Study II.

STUDY IV - Effects of Cultivation on Sod Rooting, Soil Pore Size Distribution, Soil Bulk Density and Soil Strength.

Sod Rooting

The force required to lift the sod rooting boxes is presented in Table 7. Results show that cultivation under the low (M1) soil moisture regime (2-4 % soil moisture by weight), solid tine coring (STC) and hollow tine coring (HTC) resulted in a greater lifting force as compared to the check. In contrast, rototilling (ROT) showed no difference from the check. The STC plot required 25 % and HTC plot 16 % more force to lift the rooting box as compared to ROT. Thus STC and HTC cultivations were effective in alleviating compaction under the low (M1) moisture regime.

Under the medium (M2) moisture regime (4-8 %) at the time of treatment, HTC cultivation required more force to lift the rooting box as compared to STC and ROT and was significantly higher than the check plot. The lifting force on the STC plot declined by 22 % under M2 as compared to M1. This decline in lifting force probably occurred because coring with solid tines is less effective on moist soil. There was no change in the lifting force on the HTC plot under M2 while ROT showed a slight increase compared to the M1 treatment.

Cultivation under higher (M3) moisture conditions resulted in no significant differences among treatments although there were

Table 7. Effects of moisture regime at time of cultivation[†] on force required to lift sod rooting boxes. STUDY IV. Treatments initiated 7/14/88 and extracted 6/9/89

Treatments	Soil Moisture Level		
	M1	M2	M3
	---- Mean Lifting Force ** (Kg) ----		
Check	80.8 c*	79.4 b	76.6 abc
Hollow tine coring	96.1 ab	97.7 a	97.2 a
Solid tine coring	103.8 a	84.8 ab	84.8 ab
Rototilling	83.1 bc	89.0 ab	94.0 a

* Any two means with the same letter are not significantly different at p=.05 by Duncan's Multiple Range Test.

** Extraction of rooting box at 14.7 % soilmoisture by weight.

† M1 = 2-4 %, M2 = 4-8 %, and M3 = 8-12 % soil moisture by weight.

relatively large differences among treatment means. Higher variability in the data apparently reduced the significance among means compared to Studies I and V.

Although data among moisture levels cannot be compared statistically, interesting trends occurred. There was essentially no change in lifting forces for the check and hollow tine coring plots across the moisture levels. In contrast, the lifting force for STC plots decreased between the low and medium moisture levels while the lifting forces for rototilling treatments increased with each moisture regime. This suggests better rooting resulted with STC on dry soils while rototilling is better performed on soils under more moist conditions. It was observed during cultivation that ROT under dry soil conditions tended to break up the compacted soil into a fine granular, and powdery structure, but under moist conditions, more fine angular blocky, crumb structures were formed.

These results show that STC cultivation is most effective in alleviating soil compaction and promoting root development under the M1 moisture regime. It is less effective when the soil has more than 4 % moisture by weight. Rototilling, on the other hand, may result in recompaction of soil when cultivated under dry soil conditions (2-4 % moisture by weight). However, rototilling under moist conditions (M2 and M3) apparently eases recompaction problems. Cultivation by HTC appears to be effective in alleviating soil compaction and enhancing rooting under all three moisture regimes (M1, M2, and M3).

Pore Size Distribution

Soil aeration occurs primarily by diffusion through the large pores of the soil (Beard, 1973). Macropores (0 to -100 kPa range) provide the main channels for infiltration and drainage of water and aeration, while micropores (> -100 kPa) provide for the retention of water and solutes (Hillel, 1982).

Soil pore size was determined by using moisture potential ranging from 0 to -1 kPa (very large pores), -1 kPa to -6 kPa (large pores), 0 to -100 kPa (total macropores) and -100 kPa to oven dry at 105° C (micropores).

Cultivation effects on pore size distribution are presented in Table 8 (soil samples collected prior to sodding) and Table 9 (soil samples collected at the end of the study). The data in Table 8 show that under the low moisture regime (2-4 % soil moisture by weight) hollow tine coring (HTC) and solid tine coring (STC) significantly increased very large pores (0 to - 1 kPa). This was expected because the HTC cultivation removes soil cores from the ground and STC cultivation tends to shatter dry soil. This was based on observations made at the time of treatment. Rototilling (ROT) did not increase the amount of very large pores. All three cultivation treatments (HTC, STC, and ROT) were effective in increasing large pore spaces (-1 kPa to -6 kPa). Both STC and ROT cultivations resulted in a 100 %

Table 8. Effects of cultivation under three moisture regimes[†] on the pore size distribution determined within various moisture potential ranges. STUDY IV. Treatments initiated 7/14/88 and soil samples collected 8/2/88 (prior to sodding).

Moisture Regime	Treatments	Moisture Potential Range (- kPa)				
		0 - 1	1-6	0-100	>100	Total
		------- % Porosity -------				
M1	Check	2.1	3.1	9.9	17.9	27.8
	Hollow tine coring	4.1*	5.8*	15.2*	16.1	31.3*
	Solid tine coring	3.3*	6.7*	15.0*	17.4	32.3*
	Rototilling	2.4	6.2*	14.6*	15.6*	30.4*
M2	Check	2.0	4.0	11.6	18.6	30.2
	Hollow tine coring	2.4	4.4	12.8	16.8	29.5
	Solid tine coring	2.5	4.7	12.5	17.5	30.1
	Rototilling	2.8	7.4*	15.9*	16.4	32.3
M3	Check	1.8	3.1	9.0	19.8	28.8
	Hollow tine coring	3.4	4.7	13.3	17.4	30.6
	Solid tine coring	2.9	5.2	13.0	17.6	30.6
	Rototilling	2.3	7.3*	14.6*	16.3	30.9

* Significant difference from the check at .05 level by Duncan's Multiple Range Test within a given moisture regime.

† M1 = 2-4 %, M2 = 4-8 %, M3= 8-12 % soil moisture by weight.

Table 9. Effects of cultivation under three moisture regimes† on pore size distribution determined within various moisture potential ranges. STUDY IV. Treatments initiated 7/14/88 and soil samples collected 6/10/89 (conclusion of study).

Moisture Regime	Treatments	Moisture Potential Range (- kPa)				
		0 - 1	1 -6	0-100	>100	Total
		% Porosity				
M1	Check	2.1	2.0	9.2	19.5	27.7
	Hollow tine coring	1.6	2.2	8.2	20.1	28.3
	Solid tine coring	2.2	1.9	9.2	20.3	29.6
	Rototilling	1.9	3.2	10.0	19.6	29.6
M2	Check	2.2	2.5	9.6	18.9	28.5
	Hollow tine coring	2.3	1.8	8.6	20.6	29.2*
	Solid tine coring	1.8	1.9	8.7	19.2	27.9
	Rototilling	2.5	2.4	10.1	20.5	30.6*
M3	Check	1.9	2.6	9.6	18.9	28.5
	Hollow tine coring	1.8	2.0	9.0	20.0	29.0
	Solid tine coring	2.3	1.8	9.3	20.8	30.1
	Rototilling	2.2	2.2	9.1	20.1	29.2

* Significant difference from the check at .1 level by Duncan's Multiple Range Test within a geiven moisture regime.

† M1 = 2-4 %, M2 = 4-8 %, M3 = 8-12 % soil moisture by weight.

increase in the percentage of large pores compared to the check while HTC cultivation increased large pores by 87 % under the low moisture regime.

In the 0 to -100 kPa range (total macropores) all three cultivation treatments significantly increased percent macroporosity (13.6 to 14.2 %) when compared to the check. However, ROT cultivation reduced micropores significantly ($p=.05$) by 12.5 %, while HTC cultivation also reduced micropores ($p=.1$) by 11 %. The data also showed that under the M1 moisture regime, all cultivation treatments significantly increased total porosity as shown in Table 8.

Under the M2 moisture regime (4-8 % moisture by weight), cultivation treatments did not affect very large pores. Only ROT cultivation increased large pores significantly by (38 %) and total macropores by (37 %) when compared to the check. All cultivation treatments reduced micropores by 6 to 12 % but differences were not significant. The cultivation effect on pore size distribution under M3 (8-12 % moisture by weight) moisture regime appeared to follow the same pattern as M2.

The results show that cultivation is effective in increasing macroporosity, particularly on dry soil. The increase in macroporosity should improve aeration or gas exchange and therefore enhance healthy root growth. These results are quite well correlated with the sod rooting data in Table 7.

At the end of the study, another set of soil core samples was collected June 10, 1989 and the results are presented in Table 9. Few differences were evident among treatments. Cultivation by ROT under the medium moisture regime which had significantly higher in macroporosity (0 to -100 kPa) when compared to HTC and STC. However, all three cultivation treatments were not significantly different when compared to the check. Total porosity of HTC and ROT plots were significantly different when compared to the check (p=.1).

The changes in percent pore space which occurred between time of sodding (8/2/88) and the conclusion of the study (6/10/89) are presented in Table 10. The results show that the increase in macroporosity at the initiation of study attributed to cultivation declined dramatically by the conclusion of the study. Under the low moisture regime (M1), hollow tine, solid tine and rototill cultivation treatments declined by 46, 36, and 32 %, respectively, while the check declined only by 7 %. In contrast, microporosity of HTC, STC, and ROT plots increased by 25, 17, and 23 %, respectively. The overall total porosity of the cultivation plots declined by 3 to 10 % as compared to the check (Table 10). This pattern and magnitude of changes in percent pore space were also evident under the medium and higher moisture regimes (M2 and M3, respectively).

The study shows that cultivation can be effective in increasing macropores, but only on a short term basis. This short

Table 10. Change in percent pore space which occurred between time of sodding (8/2/88) and conclusion of the study (6/10/89). STUDY IV. Soil samples collected 8/2/88 and 6/10/89.

Moisture Regime[†]	Treatments	Macropores	Micropores	Total Porosity
		----	% Porosity Change	----
M1	Check	- 7	+ 9	0
	Hollow tine coring	-46	+25	-10
	Solid tine coring	-36	+17	- 8
	Rototilling	-32	+23	- 3
M2	Check	-17	+ 2	- 6
	Hollow tine coring	-31	+23	- 1
	Solid tine coring	-30	+10	- 7
	Rototilling	-36	+25	- 5
M3	Check	+ 7	- 5	- 1
	Hollow tine coring	-32	+15	- 5
	Solid tine coring	-28	+18	- 2
	Rototilling	-38	+23	- 6

[†] M1 = 2-4 %, M2 = 4-8 %, and M3 = 8-12 % soil moisture by weight.

term benefit should allow better root growth and development shortly after sodding.

Bulk Density

Bulk density data at the beginning of the study are shown in Table 11. The check plot had an initial soil bulk density of 1.82, 1.81 and 1.78 g cc^{-1} under M1 (2-4 % moisture by weight), M2 (4-8%) and M3 (8-12 %) moisture regimes, respectively. Under the M1 moisture regime, all three cultivation treatments significantly reduced bulk density. Cultivation by STC reduced bulk density by 6.6 %, while HTC and ROT cultivations each caused a 4.9 % reduction. Under the M2 moisture regime, HTC and ROT cultivations significantly lowered bulk density, each by 5.5 %. Under M3 however, only ROT cultivation significantly reduced bulk density (by 4.5 %).

These results show that under drier soil conditions (2-4% moisture by weight), STC cultivation is most effective in lowering bulk density although there were no significant differences among cultivation treatments. This finding correlated well with the increase in total porosity due to STC cultivation and with rooting results. On the other hand, under the higher moisture regime (M3), ROT cultivation appeared to be most effective in lowering bulk density. The bulk density of 1.70 g cc^{-1} is significantly lower as

Table 11. Effects of cultivation on bulk density under three moisture regimes. STUDY IV. Treatments initiated 7/14/88 and soil samples collected 8/2/88 (prior to sodding).

Treatments	Moisture Regimes†		
	M1	M2	M3
	------- Bulk Density (g cc^{-1}) -------		
Check	1.82	1.81	1.78
Hollow tine coring	1.73*	1.71*	1.75
Solid tine coring	1.70*	1.73	1.75
Rototilling	1.73*	1.71*	1.70*

* significant difference from the check at .05 level by Duncan's Multiple Range Test within a given moisture regime.
† M1 = 2-4 %, M2 = 4-8 %, and M3 = 8-12 % soil moisture by weight.

Table 12. Effects of cultivation on bulk density under three moisture regimes. STUDY IV. Treatments initiated 7/14/88 and soil samples collected 6/10/89 (end of study).

Treatments	Moisture Regimes†		
	M1	M2	M3
	------- Bulk Density (g cc^{-1}) -------		
Check	1.82 NS*	1.82 NS	1.80 NS
Hollow tine coring	1.83	1.80	1.82
Solid tine coring	1.80	1.79	1.83
Rototilling	1.79	1.81	1.79

* No significant differences among means in columns.
† M1 = 2-4 %, M2 = 4-8 %, and M3 = 8-12 % soil moisture by weight.

compared to other treatments (Table 11). Lowering of bulk density resulted in an increase in porosity. This relationship was reflected in the pore size distributions shown in Table 8.

Bulk density data for 1989 (end of study) are shown in Table 12. No significant differences in bulk density were observed among treatments at the end of the study. This shows that the reduction in bulk density is only short term. The reason may be due to: 1) the instability of the soil structure created by cultivation, 2) low O.M. in the soil, and 3) resettling of soil particles.

Penetrometer Readings

The penetrometer readings taken August 3, 1988 (prior to sodding) and June 10, 1989 (end of study) are shown in Tables 13 and 14, respectively. When taking penetrometer readings prior to sodding, the penetrometer probe could not penetrate deep into the soil because the soil was fairly dry. Consequently, the penetration was limited to 2 cm in the check plot. The depth of penetration of the probe varied from treatment to treatment as shown in Table 13. Due to too many missing data, statistical analysis could not be performed. Nevertheless, some inferences can be made based on the available data. It is quite apparent that the force required to press the penetrometer probe into the cultivated plots is much lower than the check. This pattern is consistent

Table 13. Effects of cultivation on soil strength under three moisture regimes as measured with a penetrometer STUDY IV. Treatments initiated 7/14/88 and readings* made 8/3/88 (prior to sodding).

Moisture Regime	Treatments	Soil Depth (cm)							
		1	2	3	4	5	6	7	8
		------- Soil Strength (Newton) ------							
M1[†]	Check	8	432	-	-	-	-	-	-
	Hollow tine coring	14	206	274	-	-	-	-	-
	Solid tine coring	9	61	108	109	233	-	-	-
	Rototilling	8	90	216	320	-	-	-	-
M2	Check	8	432	-	-	-	-	-	-
	Hollow tine coring	17	191	266	333	363	-	-	-
	Solid tine coring	7	194	302	376	-	-	-	-
	Rototilling	15	101	223	351	-	-	-	-
M3	Check	8	432	-	-	-	-	-	-
	Hollow tine coring	16	110	162	196	23	-	-	-
	Solid tine coring	13	78	164	200	-	-	-	-
	Rototilling	13	79	130	188	289	-	-	-

† M1 = 2-4 %, M2 = 4-8 %, and M3 = 8-12 % soil moisture by weight.
* Penetrometer readings at 8-10 % soil moisture by weight.

Table 14. Effects of cultivation on soil strength under three moisture regimes as measured with a penetrometer. STUDY IV. Treatments initiated 7/14/88 and readings** made 6/16/89 (conclusion of study).

Moisture Regime†	Treatments	Soil Depth (cm)							
		1	2	3	4	5	6	7	8
		------- Soil Strength (Newton) ---- -							
M1	Check	15	206	283	313	328	346	369	387
	Hollow tine coring	12	204	260	284	292	309	320	323
	Solid tine coring	21	196	243	253*	266*	285	323	360
	Rototilling	7*	164	208*	230*	242*	229	283	319
M2	Check	24	215	270	293	307	310	318	332
	Hollow tine coring	22	188	234	247	252	255	276	308
	Solid tine coring	16	205	249	264	276	300	316	322
	Rototilling	29	201	247	287	295	299	330	351
M3	Check	16	214	280	304	318	331	344	364
	Hollow tine coring	18	206	253	265	271	287	298	339
	Solid tine coring	25	181	246	266	289	305	316	327
	Rototilling	14	182	263	281	296	312	293	324

* Significant difference from the check at .05 level by Duncan's Multiple Range Test within a given moisture regime.

† M1 = 2-4 %, M3 = 4-8 %, and M3 = 8-12 % soil moisture by weight.

** Penetrometer readings at 14.7 % soil moisture by weight.

throughout the three moisture regimes. Based on this observation, it is assumed that cultivation is effective in lowering the soil strength.

The second set of data on penetrometer readings was collected at the end of the study and is presented in Table 14. Due to the wet weather conditions, the soil had a moisture content of 14.7% by weight. Consequently, the penetrometer probe penetrated deeper than at the initiation of the study. The ROT cultivation plots under M1, showed significantly lower soil strengths at several depths compared to the check plot. The STC cultivation plot showed significant differences at 4 and 5 cm depths. No significant differences occurred among all treatments under the M2 and M3 moisture regimes, although soil strengths are slightly lower than the check at several depths.

Based on the findings of this study, it is clear that cultivation is effective in reducing bulk density and possibly soil strength, as well as increasing porosity, particularly the large pores. However, all these physical changes generated by cultivation are short-lived.

SUMMARY

These studies show that cultivation of sites which are to be sodded can promote better root development based on the results of the force that was required to lift the rooting boxes. Compaction, on the other hand, was found to impede root development compared to uncultivated conditions.

Soil moisture content at the time of cultivation had a profound influence on sod rooting response. Solid tine cultivation appeared to be more beneficial to rooting when done under low soil moisture conditions (2-4 % by weight). Rototill cultivation was more conducive to sod rooting when executed under moist soil conditions (8-12% by weight). However, rototilling at low soil moisture content initially showed a positive effect on sod rooting, but at the conclusion of the studies, this advantage was reduced or negated. This suggested the rototilled soil had recompacted again. Sod rooting on hollow tine cored plots was satisfactory under the low and medium soil moisture regimes (2-8 %).

Cultivation had a positive effect on reducing soil strength. This trend was noticeable at all soil moisture content (2-12 % by weight) levels studied. However, lowering of soil strength by

cultivation was a short term response only, no differences were found in soil strength at the conclusion of the study (10 months after treatment).

Cultivation treatments also had a profound influence on soil bulk density and pore spaces, particularly on the large pore spaces (-1 kPa to -100 kPa). Soil moisture content during cultivation affected bulk density. Solid tine coring was more effective in reducing bulk density under the low moisture regime (2-4 % by weight) than under medium to higher moisture regimes. Hollow tine coring was effective in lowering bulk density under low to medium soil moisture regimes (2-8 %), but less effective when soil moisture exceeded 8 % by weight. In contrast, rototill cultivation was effective over a wider range of soil moisture content (2-12 %). Although all cultivation treatments were effective in reducing soil bulk density, the effect again appeared to be short term only. At the conclusion of the study there was no difference in bulk density attributed to treatment.

Soil porosity data indicated that all three cultivation treatments were effective in increasing macroporosity (-1 kPa to -100 kPa) and reducing microporosity (-100 kPa to Oven dry at 105° C) initially. However, that trend was reversed at the conclusion of the studies, with essentially no difference among treatments in pore size distribution.

Sod rooting benefitted from the short term increase in macroporosity and the reduction in bulk density and soil strength.

Over the longer term the improvement in soil properties was lost although there was still an advantage in sod rooting. This points out the benefits of cultivation of the soil where sod is to be laid which are both short term (soil and rooting) as well as long term (rooting). A key factor in proper soil preparation is soil moisture at the time of cultivation. The drier the soil, the greater the short term improvement in soil properties, especially when cultivating by rototilling.

Based on sod rooting responses, cultivation with vertical operating equipment is a viable means of preparing the soil for sodding on compacted subsoils.

Soil amendments and wetting agents were not effective in the relief of soil compaction or stimulation of improved root growth, as utilized in this studies. More time would be needed to determine whether these products can improve soil properties.

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