This is to certify that the

thesis entitled

Hollow and Solid Tine Effects on Soil Structure and Turfgrass Root Growth

presented by

James A. Murphy

has been accepted towards fulfillment of the requirements for

M.S. degree in *Crop & Soil Sciences*

[signature]

Major professor

Date *July 28, 1986*

REMOTE STORAGE RSF

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.

DATE DUE	DATE DUE	DATE DUE
MAY 15 2013 [illegible]		

HOLLOW AND SOLID TINE CULTIVATION EFFECTS ON SOIL STRUCTURE AND TURFGRASS ROOT GROWTH

By

James Arthur Murphy

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Crop and Soil Sciences

1986

ABSTRACT

HOLLOW AND SOLID TINE CULTIVATION EFFECTS ON SOIL STRUCTURE AND TURFGRASS ROOT GROWTH

By

James Arthur Murphy

Hollow and solid tine cultivation effects as influenced by soil compaction and moisture content during cultivation were evaluated on the basis of soil structural qualities and root growth over a 2 year period. As expected compaction resulted in pronounced detrimental effects on soil structure and root growth. Both cultivation methods resulted in positive and negative effects on soil structure. While cultivation increased the amount of large soil pores drained between 0 and -0.001 MPa, a corresponding decrease in the remaining macropores drained between -0.001 and -0.010 MPa occurred in noncompacted soil. Regardless of compaction levels, solid tine cultivation increased the amount of micropores drained between -0.010 and -0.100 MPa compared to hollow tine cultivation. Water conductivity dropped dramatically with cultivation in noncompacted soil. Cultivation reduced surface soil strength. Initially, solid tine cultivation was more effective in loosening the surface soil than hollow tine cultivation, however this effect was reversed by the end of this study. Cultivation decreased surface rooting in noncompacted soil but had no influence on rooting in compacted soil. Greenhouse studies demonstrated the potential for cultivation to enhance rooting within the tine hole while limiting root development below the tine hole.

to my family,
especially Carol,
for their love, support, and patience

ACKNOWLEDGEMENTS

I wish to express a sincere thanks to Dr. P. E. Rieke, chairman of my guidance committee, for his guidance, support and patience during the good times and bad. I am most grateful to Dr. A. E. Erickson, Dr. B. E. Branham, and Dr. J. M. Vargas for their valuable assistance and advice as members of my guidance committee. I also wish to thank Micheal Ferkowicz for his unending perserverance and assistance during this investigation. I would like to thank my fellow graduate students, especially Roch Gaussoin, for their support which made my program most rewarding.

Lastly, I would like to acknowledge the United States Golf Association and Michigan Turfgrass Foundation for their finacial support of this investigation.

TABLE OF CONTENTS

LIST OF TABLES

INTRODUCTION

Most recreational turf areas experience a high frequency of use. Associated with this usage are both vehicular and foot traffic. Either form of traffic can result in soil compaction. Soil compaction can also occur during construction on such sites as golf courses and home lawns.

Soil compaction decreases soil porosity with resultant increases in bulk density. As soil porosity decreases, particularly macroporosity, reductions in soil water movement, aeration, and turfgrass shoot and root growth can occur which lower the functional quality of the turf. Few alternatives are available for alleviating the problems associated with compacted soils because significant loosening of the soil cannot be accomplished without major disruption of the turf.

Core cultivation, or aerification, is the most widely used practice for improving compacted soil conditions under turf. Core cultivation has traditionally referred to the mechanical removal of soil cores (plugs) from established turf. In recent years, solid tine cultivation has received attention as being a possible practice in combatting soil compaction in turfgrass management. Solid tine cultivation eliminates soil core processing time and labor requirements associated with hollow tine cultivation. However, little is known about the direct effects of solid tine cultivation on soil physical properties and turfgrass root growth.

LITERATURE REVIEW

Compaction

The soil is a medium for plant growth and as such, its structure should not hinder the movement of water, oxygen and nutrients to plant roots. Unfavorable soil structure has the characteristics of increased soil density and decreased aeration which restrict seedling development and root proliferation (Baver et al., 1972). Soil structure can deteriorate in highly trafficked areas.

Hillel (1980) described soil compaction as the compression of an unsaturated soil body reducing the soil fractional air volume. The degree to which a soil will compress is a function of the soil moisture content, antecedent bulk density, magnitude of the compactive effort and soil texture (Free et al., 1947; Reaves and Nichols, 1955). Forces which compact soil can originate from natural sources such as rainfall and wetting and drying cycles or mechanical sources such as traffic from people and machinery (Harris, 1971).

Recreational turf areas are subjected to high usage. With the passage of people and machinery over the same sites soil compaction is an inevitable problem in turfgrass management. Madison (1971) has stated, "compaction is the foremost turf problem."

Soil Responses

Aeration porosity and bulk density are commonly used measures to characterize soil structure and compaction phenomona. Compactive efforts on a soil can result in decreased soil porosity (Proctor, 1933). A decrease in soil porosity has the associated effects of increased soil density (Tanner and Mamaril, 1959). A reduction in total porosity, as a result of compaction, is generally at the expense of the soil aeration porosity. Aeration porosity refers to those pores not filled with water at a given moisture tension. Swartz and Kardos (1963) observed a decrease in aeration porosity from 19.3% at the lowest level of compaction to 12.7% at the highest level compaction on several sand-soil-peat mixes differing in moisture content at the time of compaction. Capillary porosity increased from 32.2% at the lowest compaction level to 35.7% at the highest level. Water retention characteristics are influenced with alterations of soil porosity. Relative to noncompacted soil, compacted soil will generally retain greater amounts of water at a given soil matric tension as a result of increased microporosity (Baver, 1938; O'Niel and Carrow, 1982; Sills and Carrow, 1982). However, it is possible that both aeration porosity and microporosity can be reduced by compaction thereby reducing water retention at any given matrix suction (Agnew and Carrow, 1985).

Alteration of the soil porosity by compaction can influence soil water movement. Baver (1938) demonstrated soil water permeability to be a function of macroporosity; as macroporosity decreased so did water permeability. Swartz and Kardos (1963) found percolation rates decreased substantially with compaction. In their study aeration porosity had a strong positive correlation with percolation rate. Akram and Kemper (1979) found infiltration rates were lowered as compacting forces and/or soil moisture content at compaction increased. Infiltration rates of a loamy sand were reduced from 20 to 0.5 cm hr^{-1} as soil water content was increased from air dry to 1.3 times field capacity at the time of a .339 MPa compacting force.

Soil oxygen movement is reduced with compaction. Agnew and Carrow (1985) found oxygen diffusion rates (ODR) in compacted soil remained below the 20 x 10^{-8} gm cm^{-2} min^{-1} value, considered threshold for adequate plant growth, for as long as 143 and 119 hours after irrigation at the 7.5 and 15 cm depths, respectively. Noncompacted soil reached acceptable levels within 26 and 50 hours at the 7.5 and 15 cm depths, respectively. These observations were consistent with the findings of O'Niel and Carrow (1983). Asady et al. (1985) found ODR in a Charity clay at -0.008 MPa soil moisture potential decreased from 49.0 to 10.0 gm cm^{-2} min^{-1} as soil density increased from 1.39 to 2.1 g cc^{-1}. This reduction in ODR also coincided with a decrease in air-filled porosity from 31.0 to 8.0%. Hughes et al. (1966) also observed reduced ODR values with soil compaction.

Increases in soil density can increase soil strength. Taylor and Gardner (1963) showed soil strength increased with bulk density and moisture suction. Taylor et al. (1966) demonstrated that soil strength of a loamy sand at -0.033 MPa moisture potential increased from .6 to 1.7 MPa as density rose from 1.55 to 1.8 g cc^{-1}. Others have observed increases in mechanical resistance as soil density increases (Asady et al., 1985; Hughes et al., 1966; Tanner and Mamaril, 1959).

Shoot Responses

Compaction can reduce turfgrass visual quality (Agnew and Carrow, 1985; O'Niel and Carrow, 1982; Sills and Carrow, 1982). In a field study, Carrow (1980) found a significant positive correlation between visual quality and aeration porosity at -0.010 MPa of Chase silt loam soil for tall fescue (*Festuca arundinacea* Schreb.) and perennial ryegrass (Lolium perenne L.). A significant positive correlation was also found between visual quality and bulk density for tall fescue, perennial ryegrass and Kentucky bluegrass (Poa pratensis L.).

The influence of compaction on turf shoot density, verdure (aerial shoot material remaining after mowing) and percent cover varies among species. Watson (1950) reported increased density of Kentucky bluegrass with compaction in a fairway turf consisting of bentgrass (Agrostis palustris Huds.), red fescue (Festuca rubra L.) and Kentucky bluegrass. In studies conducted on monostands, shoot densities of perennial ryegrass and Kentucky bluegrass have declined under compaction stress (Carrow, 1980; O'Niel and Carrow, 1982; O'Niel and Carrow, 1983). However, shoot densities of tall fescue were not significantly altered by soil compaction stress (Carrow, 1980; Sills and Carrow, 1982).

Verdure of Kentucky bluegrass, common bermudagrass (Cynodon dactylon (L.) Pers.) and tall fescue decline with compaction stress (Agnew and Carrow, 1985; Carrow, 1980; O'Niel and Carrow, 1982; Thurman and Porkorny, 1969). In contrast, in another study Sills and Carrow (1982) reported no effect of compaction on verdure of tall fescue. Compaction has had no influence on verdure of perennial ryegrass (Carrow, 1980; O'Niel and Carrow, 1983; Sills and Carrow, 1983).

In a field study Carrow (1980) observed the percent cover of mature tall fescue and Kentucky bluegrass turfs were reduced up to 8 months after the last compaction treatment. Perennial ryegrass cover was not affected in this study.

Clipping yields decline under compaction stress (Thurman and Pokorny, 1969; Rimmer, 1969; Valoras et al., 1966). O'Niel and Carrow (1983) reported total clipping yields of perennial ryegrass declined 38 and 53% under moderate and heavy compaction, respectively when compared to noncompacted turf. Compaction stress can reduce clipping yields within 8 days on a Kentucky bluegrass stand (Agnew and Carrow, 1985). Schmidt (1980) found spring clipping yields were greater on heavily compacted plots compared to lightly compacted plots. The reverse was true during the summer.

Carrow (1980) found total nonstructural carbohydrates (TNC) declined for Kentucky bluegrass, perennial ryegrass and tall fescue as compaction stress was applied. However, subsequent studies have not shown TNC levels to be affected by compaction stress (O'Niel and Carrow, 1982; Sills and Carrow, 1982; Sills and Carrow, 1983).

<u>Root Responses</u>

Reported effects of compaction on root growth have been somewhat conflicting. Watson (1950) found no compaction effect on root development of a mixed species fairway turf. In a field study utilizing monostands, Carrow (1980) observed declining root growth of Kentucky bluegrass with compaction stress. He also noted perennial ryegrass root growth declined with moderate compaction but was not affected with heavy compaction. The decrease in rooting of perennial ryegrass under moderate compaction was associated with increased tillering. However, tall fescue root growth was not significantly affected with compaction in this study. Sills and Carrow (1982) observed that total root growth of tall fescue was reduced by compaction only when higher nitrogen fertilization rates where used.

O'Niel and Carrow (1982) reported no influence of soil compaction on root weight or distribution of a 2 year old Kentucky bluegrass stand.

In a greenhouse study O'Niel and Carrow (1983) evaluated perennial ryegrass under compaction stress and observed differences in root distribution although total root growth was not significantly affected. They found a higher percentage of roots in the surface 0 to 5 cm and a lower percentage in the 10 to 25 cm zone. Sills and Carrow (1983) observed a decline in total root growth of perennial ryegrass under compaction stress. The decline was more pronounced at higher nitrogen fertilization rates yielding a 44.6% decrease compared to noncompacted plots. Agnew and Carrow (1985) observed compaction stress over a 99 day period increased root weights in the surface 5 cm and lowered root weights in the 10 to 20 cm zone. Compaction stress over a 9 day period decreased root weights only in the 15 to 20 cm zone. Total root weights were not significntly affected by the 99 or 9 day compaction treatments.

Wilkinson and Duff (1972) compared rooting of annual bluegrass (*Poa annua* L.), creeping bentgrass and Kentucky bluegrass at three soil densities under growth chamber conditions and found no differences among species, although root growth significantly increased for all species as soil density increased from 1.1 to 1.4 g cc^{-1}. They attributed the increase in root growth to increased water availibility at higher densities and the use of a sandy loam soil which prevented soil oxygen from being limiting.

Inadequate soil aeration and mechanical impedance are important factors associated with poor root growth in compacted soils. Compaction can produce poor soil aeration. Letey et al. (1966) found common bermudagrass root growth was greatly reduced or stopped by ODR values less than 15×10^{-8}g cm^{-2} min^{-1}. An ODR value of 20×10^{-8}g cm^{-2} min^{-1} was reported to be limiting for Newport Kentucky bluegrass (Letey et al, 1964). Waddington and Baker (1965) found Merion Kentucky bluegrass required ODR values of 5 to 9 x 10^{-8}g cm^{-2} min^{-1} for adequate root growth while creeping bentgrass and goosegrass grew well at ODR values as low as 5 x 10^{-8} g cm^{-2} min^{-1}. Grable and Siemer (1968) studied the effects of bulk density, aggregate size and soil water suction on oxygen diffusion and corn (Zea mays L.) root elongation. Over the range of 0 to 68 cm of water suction they found diffusion of oxygen controlled the rate of root elongation. They noted oxygen diffusion was determined by air porosity and suggested 12 to 15% air porosity was needed for adequate plant growth. Also, root elongation rates tended to decrease at 48 to 68 cm of water suction. Reasons for the decrease were suggested to be due to increased soil strength.

Compaction can result in greater mechanical impedance to root growth. No information is available on turfgrass root development in response to mechanical impedance. However, several investigators have evaluated agronomic crop responses to mechanical impedance and were summarized by Lutz (1952). 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. The lowest density where roots failed to penetrate was 1.46 g cc^{-1} for an Aiken clay loam. They concluded roots failed to penetrate soil due to small pore sizes rather than to a reduction in oxygen supply. Wiersum (1957) examined the relationship between size and structural rigidity of pores and root penetration. Roots can enter pore sizes of smaller diameter than the young root itself only if rigidity of the pore structure is weak enough to allow soil displacement.

In examining cotton (Gossypium hirsutum L.) taproot penetration as influenced by bulk density, moisture content and soil strength, Taylor and Gardner (1963) found a highly significant negative correlation between soil strength and root penetration into prepared cores; as soil strength increased root penetration declined. They found no root penetration when soil strength was 2.96 MPa as measured by a static penetrometer. In another study Taylor et al. (1966) found cotton taproot penetration decreased drastically as soil strength increased to 2.50 MPa. With higher strength levels no root penetration occurred.

Rickman et al. (1966) evaluated tomato (Lycopersicon esculentum L.) root response to oxygen supply and physical resistance. They proposed ODR to be the primary factor in limiting root growth even though the high density - high ODR (artificially maintained) treatment did slow root growth. In a similar study Tackett and Pearson (1964) found mechanical impedance was more detrimental than low oxygen at densities greater than 1.5 g cc^{-1}. At densities lower than 1.5 g cc^{-1} oxygen levels below 10% restricted cotton seedling root penetration. However, root restriction was greater with high bulk densities.

Cultivation

Cultivation is one practice used to combat soil compaction on high use turf sites, such as athletic fields, parks and golf courses. Other management practices used are soil modification and/or traffic control.

Turf cultivation refers to the selective tillage of an established turf without excessive disruption of the turf (Beard, 1973). There are several forms of turf cultivation, such as coring, slicing, spiking and deeper subaerification (Turgeon, 1980). The most frequently used method is core cultivation. In particular, the vertical operating tine (VOT) units are used extensively in golf course turf management systems.

Core cultivation involves the removal of soil cores from established turf to alleviate problems of soil surface compaction, layering and thatch accumulation. Evidence to support these objectives is limited and somewhat conflicting. Murray and Juska (1977) reported reduced thatch accumulation, reduced leaf spot damage and improved turf quality in a one year cultivation study. Engel and Alderfer (1967) found no significant influence on thatch accumulation, overall turf quality or water penetration from core cultivation over a ten year period. They noted a slight increase in ODR with cultivation.

Infiltration rates have increased (Waddington, 1974), decreased (Roberts, 1975) and remaimed unchanged (Byrne, 1965) as a result of coring. Alderfer (1954) reported a significant reduction in runoff on compacted aerified plots when compared to nonaerified plots. However, coring did not increase the clipping yield of the Kentucky bluegrass stand growing on compacted soil. Cordukes (1968) observed enhanced turfgrass recovery from compaction with aerification. In a 2 year field study Petrovic (1979) found core cultivation had little influence on turf quality, soil strength and oxygen diffusion rates. Studies have shown no appreciable increase in turfgrass root development with cultivaton (Engel, 1951; Harper, 1953).

Alleviation of soil compaction is often the primary objective of core cultivation, however, destruction of soil structure may occur due to localized soil compaction (Engel, 1970). Petrovic (1979) examined soil density changes caused by penetration of hollow tines into laboratory prepared soil cores. With the use of computed axial tomographic (CT) scanning, large bulk density increases in the soil surrounding the coring hole were observed. Under greenhouse conditions, the zone of increased bulk density at the bottom of the coring hole was still evident after 93 days while compaction at the sidewall zone had dissipated due to the walls collapsing. These findings support Engel's (1970) suggestion of the deleterious effect of cultivation on soil structure. Therefore, it is proposed that routine cultivation in turf management programs might lead to induced hardpans below the cultivation zone. Petrovic (1979) also noted that smaller increases in bulk density due to tine penetration occurred in higher density soil. He thereby concluded that higher density soils maybe less suseptible to the compacting effects of core cultivation.

Increasing interest has developed regarding the replacement of hollow tines with solid tines in standard cultivation operations. Reasons for the increased popularity of this practice stem from the dramatic savings in time and labor costs. Solid tine cultivation eliminates the need for soil core removal required with the traditional hollow tine practice. However, the response of turf to solid tine cultivation has not been recorded.

Therefore, the objectives of this research were to determine the effects of vertically operating hollow and solid tine cultivation on soil structure and turfgrass root growth as influenced by soil compaction and soil moisture at the time of cultivation.

MATERIALS AND METHODS

Field Study

A vertically operating tine (VOT) cultivation study was initiated in May, 1984 at Michigan State University Robert Hancock Turfgrass Research Center on a 3 year old Penncross creeping bentgrass turf maintained under greens conditions. The soil under this turf was a modified loamy sand containing 83.5% sand, 10.6% silt and 5.9% clay.

A 2 x 2 x 2 factorially arranged randomized complete block design was used. One check at each compaction level was also included for comparison. Factors included compaction, tine type and soil moisture at the time of cultivation. Compaction levels were: (i) NC = noncompacted except for normal maintenance practices and (ii) C = compacted with a Ryan's Rollaire vibrating power roller. Static pressure of the roller when filled with water was 0.52 kg cm^{-2}. Compaction treatment consisted of 6 passes per plot. The two tine types were 1.25 cm O.D. (i) hollow and (ii) solid tines. Cultivation was performed with a Ryan's Greensaire II at moisture levels of (i) Moist = an average soil moisture potential of -0.050 MPa and (ii) Wet = -0.003 MPa average moisture potential as measured with tensiometers (Marthaler et al, 1983) placed at the 2.5 to 7.5 cm depth zone (zone of cultivation). All plots were subjected to dry down prior to the moist cultivation treatments. Following moist cultivation treatments irrigation was applied over a 2 to 3 day period to rewet all plots to -0.003 MPa for wet cultivation treatments.

In 1984 compaction treatments averaged 6 passes per week May 11 through August 14 totaling 90 passes. One set of cultivation treatments was applied; moist cultivation on August 27 and wet cultivation on August 30. Moisture sampling at the time of cultivation operations yielded an average 7.5 and 19.1% soil moisture content by weight at -0.050 and -0.003 MPa, respectively.

In 1985, 32 compaction treatments were performed May 1 through Sept 14 totaling 192 passes. Three sets of cultivation treatments were performed. Moist cultivation treatments were applied on June 4, July 13 and August 14 at average gravimetric moisture contents of 8.8, 9.1 and 9.7 %, respectively. Wet cultivation treatments were applied on June 6, July 15 and August 16 at average gravimetric moisture contents of 21.5, 25.3 and 17.7 %, respectively.

Total nitrogen applied was 119.8 kg ha^{-1} and 130.7 kg ha^{-1} in 1984 and 1985, respectively. Fungicides were applied as necessary to control disease. Supplemental irrigation was applied as necessary to maintain an average soil moisture above -0.030 MPa except during drydown periods prior to moist cultivation operations. A cutting height of 0.6 cm was maintained throughout the study.

Four undisturbed soil cores, 7.6 cm I.D. x 7.6 cm deep were taken per plot for laboratory measurements of bulk density, moisture retention, air porosity, saturated hydraulic conductivity and oxygen diffusion rate (ODR) determinations in October of 1984 and 1985. Cores were excavated so that the top of each core began below the bottom of the thatch layer which positioned the bottom of the tine holes at approximately the middle of the core. Moisture retention and air porosity determinations were made at 0, -0.001, -0.010, -0.100 MPa and oven dry (105 C) moisture potentials. Saturated hydraulic conductivity measures were determined using the technique described by Klute (1965).

ODR were measured in the labarotory at water potentials of -0.002, -0.003, and -0.004 MPa by the platinum microelectrode method of Lemon and Erickson (1952). Three readings per core were taken at the 3.8 cm depth for each tension level.

A depth monitoring penetrometer (Davidson, 1965) was used to take 10 readings per plot on September 3, 1984 and November 27, 1985 at soil moisture potential greater than -0.05 MPa.

Infiltration rates were determined in September, 1984 using a constant head double ring infiltrometer technique; 12.7 cm inside ring and 22.9 cm outside ring. Both rings were driven to a 7 cm depth into the soil. A 1.25 cm constant head was maintained in both rings during infiltration runs. Infiltration runs lasted 4 hours and the final 3.5 hours were used to calculate hourly rates.

In November 1985 five root samples 4.4 cm^2 x 15 cm deep were taken per plot and sectioned at the 7.5 cm depth to form two samples. Samples were washed with the hydro-elutriation system of Smucker et al. (1982), dried at 60 C and weighed.

All data were subjected to anlysis of variance and planned comparisons were made using single degree of freedom orthogonal comparisons (Steele and Torie, 1980). In 1984 five contrasts were made evaluating the noncompacted check versus the compacted check (NC-Ck vs CD-Ck), hollow versus solid tine cultivation (T), moist versus wet soil at the time of cultivation (M), tine type by soil moisture interaction (T x M), and within compacted soil, the check versus the average cultivation effect (CD-Ck vs Cult).

In 1985 nine contrasts were planned examing the 3 main effects of no compaction versus compaction (C), hollow versus solid tine cultivaition (T), and moist versus wet soil at the time of cultivation (M), the 4 subsequent interactions C x T, C x M, T x M, and C x T x M, and within each level of compaction the check versus the average cultivaition effect (Ck vs Cult).

Greenhouse Study 1

This study, initiated April 30, 1985, was arranged in randomized complete block design with 5 replications. Three treatments consisting of a check (no tine), hollow and solid tine penetration into prepared soil cores.

The soil used was a Metea fine sandy loam consisting of 73.0% sand, 18.6% silt, and 8.4% clay. The soil was air dried and passed through a 1 mm sieve. Soil was poured at a moisture content of 1.0% by weight into 10.1 cm I.D. by 16.5 cm high polyvinyl chloride (PVC) pipe. Container bottoms consisted of filter paper and two layers of cheesecloth held in place with a rubber band. Soil was poured to fill the entire core assembly after which the top 2.5 cm section of core assembly was removed so as to level the soil remaining in the 14.0 cm high core. Soil weights ranged from 1463.5 to 1494.4 g (air dry) and were blocked according to weight. Cores were then put through two wetting and drying cycles (saturation to -0.1 MPa) after which the soil was compressed with a hydraulic press (Carver type, Model 20505-11) at -0.100 MPa to the required height to achieve a bulk density of 1.65 g cc^{-1}.

Sod plugs 10.1 cm diameter by 1.9 cm high were cut from a 3 year old Toronto creeping bentgrass turf and sodded onto saturated soil cores described above. Sod was allowed to root for 7 days into saturated soil cores. Cores were then moved to ceramic plates and a 0.030 MPa tension was maintained for 1 day followed by 2 days at 0.070 MPa tension. Coring treatments were applied on May 9, 1985 at a soil moisture content of 6.8% by weight. Treatments were applied with a gear cutting tool (Gould & Eberhardt, Model 6243) which simulated the tine movement of standard VOT cultivation equipment. Hollow and solid tines 1.25 cm O.D. were used to cultivate sodded cores creating tine holes in the center of each core 7.6 cm deep (5.7 cm into prepared soil).

Following treatment all cores were watered with 50 ml of water and returned to ceramic plates at 0.030 MPa tension to permit adequate drainage. Sod was allowed to grow for 14 days with supplemental watering applied as necessary to prevent wilting.

Cores were sampled at 2.5 cm intervals from the soil surface to the 10.0 cm depth. Within each 2.5 cm section 2 samples were taken. One sample consisted of a 2.5 cm diameter core at the center equidistant from the edges of the container walls, surrounding the tine hole. The second sample was a 7.6 cm diameter core surrounding and concentric to the 2.5 cm core yielding a doughnut shaped sample. Roots were then separated from the soil using the hydropneumatic elutriation technique of Smucker et al. (1982). After washing, the roots of each sample were counted using the line intersect method (Newman, 1966).

All data were subjected to analysis of variance and planned comparisons were made using single degree of freedom orthogonal comparisons. Two comparisons were planned contrasting the control (check) versus the average tine effect and hollow versus solid tine penetration.

Greenhouse Study 2

This study, initiated on December 22, 1985, was arranged in a randomized complete block design with 4 replications. The three treatments used in study 1 were performed at two differing moisture contents for a total of 6 treatments.

The soil used was a Metea fine sandy loam consisting of 73.0% sand, 18.6% silt, and 8.4% clay. The soil was air dried and passed through a 1 mm sieve. Soil was poured at a moisture content of 1.0% by weight into 10.1 cm I.D. by 19.1 cm high PVC pipe. Container bottoms consisted of filter paper and two layers of cheesecloth held in place with a rubber band. Soil was poured to fill the entire core assembly after which the top 2.5 cm section of core assembly was removed so as to level the soil remaining in the 16.5 cm high core. Soil weights ranged from 1778.8 to 1829.9 g (air dry) and were blocked according to weight. Cores were then put through two wetting and drying cycles (saturation to -0.070 MPa) after which the soil was compressed with a hydraulic press (Carver type, Model 20505-11) at -0.070 MPa to the required height to achieve a bulk density of 1.65 g cc^{-1}.

Sod plugs 10.1 cm diameter by 1.9 cm high were cut from a 4 year old Penncross creeping bentgrass turf and keep moist for 6 days. Sod plugs were then sodded onto saturated soil cores prepared as decribed above. Sodded cores were allowed to root for 8 days and then placed on plates at 0.030 MPa tension for 3 days. Tension was increased to 0.070 MPa for 2 days. Treatments were applied January 3, 1986 using a gear cutting tool (Gould & Eberhardt, Model 6243) and 1.25 cm diameter hollow and solid tines at soil moisture contents of 14.9 (-0.010 MPa) and 7.5% (> -0.070 MPa). Tine holes were made at the center of each core and 7.6

cm deep.

On January 4 the sod was clipped to 2.5 cm. Cores were watered every three days to -0.010 MPa moisture equivalent. Sixteen days following treatments the experiment was terminated. Cores were sectioned as described previously for root analysis.

All data were subjected to analysis of variance and planned comparisons were made using single degree of freedom orthogonal comparisons. Comparisons were planned contrasting moist versus wet soil conditions at the time of tine treatment. Two other contrasts were evaluated within each moisture level comparing the control (check) versus the average tine effect and hollow versus solid tine penetration.

RESULTS AND DISCUSSION

Bulk Density

Bulk density data for 1984 are shown in Table 1. The compacted check had significantly higher bulk density when compared to the noncompacted check in 1984 with compaction increasing density 2.3%. Cultivation resulted in 2.3% lower bulk densities than the compacted check. No differences were observed between individual cultivation treatments.

In 1985 compaction increased soil density 2.9% above noncompacted plots (Table 2). The type of tine used for cultivation also influenced soil density. Hollow tine cultivation yielded 2.3% lower bulk densities than solid tine cultivation. This tine effect can be attributed to the removal of soil with the use of hollow tines.

Aeration Porosity

No significant differences were observed in 1984 for aeration porosity at -0.010 MPa water potential (Table 1). In 1985 compaction lowered aeration porosity 17.3% below noncompacted plots (Table 2). The type of tine used for cultivating also influenced aeration porosity. Solid tine cultivation yielded 10.1% lower aeration porosity values than hollow tine cultivation across all treatments. Greater aeration porosity would be beneficial in assuring adequate oxygen supply and reduced mechanical impedance for the root system. Higher aeration porosities with hollow tine use can be attributed to the removal of soil with this practice.

Table 1. The effects of compaction, cultivation, and soil moisture during cultivation on bulk density and -0.010 MPa aeration porosity in October, 1984.

Treatments	Bulk Density	Aeration Porosity
	$g\ cc^{-1}$	%
Noncompacted (NC)		
Check (Ck)	1.74	13.9
Compacted (CD)		
Check	1.78	12.5
Hollow Moist	1.74	12.6
Hollow Wet	1.74	12.7
Solid Moist	1.76	12.3
Solid Wet	1.75	10.3
Comparisons	**Mean Squares[a]**	
NC-Ck vs C-Ck	24.00 *	2.940
Tine Type (T)	8.33	5.201
Moisture (M)	0.00	2.521
T x M	1.33	3.307
CD-Ck vs Cultivation	24.07 *	0.662
Error	4.46	2.055

* significance at the .05 level.
a-Bulk density mean squares are adjusted x 10^{-4}

Table 2. The effects of compaction, cultivation, and soil moisture during cultivation on bulk density and -0.010 MPa aeration porosity in October, 1985.

Treatments	Bulk Density	Aeration Porosity
	g cc^{-1}	%
Noncompacted (NC)		
Check (Ck)	1.74	15.5
Hollow Moist	1.72	15.7
Hollow Wet	1.71	15.4
Solid Moist	1.78	14.1
Solid Wet	1.76	15.0
Compacted (CD)		
Check	1.80	12.1
Hollow Moist	1.76	14.0
Hollow Wet	1.80	13.2
Solid Moist	1.81	11.9
Solid Wet	1.81	11.4
Comparisons	**Mean Squares[a]**	
Compaction (C)	197.63 **	50.96 **
Tine Type (T)	100.04 **	13.65 **
Moisture (M)	1.04	0.15
C x T	7.04	1.35
C x M	22.04	1.26
T x M	7.04	0.84
C x T x M	5.04	0.22
NC-Ck vs Cultivation	0.02	0.42
CD-Ck vs Cultivation	0.27	0.79
Error	7.92	1.52

** significance at the .01 level.
a-Bulk density mean squares are adjusted x 10^{-4}

Moisture Retention

Moisture retention data for 1984 are presented in Table 3. In compacted soil cultivation increased total water holding capacity at saturation (0 MPa) by 4% when compared to the compacted control. No tine or moisture effects were evident. Compaction had a slight effect ($P<0.07$) on total water holding capacity resulting in a 4% decrease when the two check plots were compared.

Cultivation resulted in significantly greater amounts of water held at -0.010 MPa. Water retention was increased 9.2% over the compacted control. Significant tine by moisture interactions were found at -0.010 and -0.100 MPa moisture potentials. Soil cultivated with solid tines under wet conditions retained 10.7 and 12.5% more moisture at -0.010 and -0.100 MPa than solid tine cultivation under drier (moist) soil conditions. Also under wet soil conditions, solid tine cultivation resulted in 10.7 and 8.7% higher moisture retention than hollow tine cultivation at -0.010 and -0.100 MPa, respectively. Soil moisture effect did not influence hollow tine cultivation. A similar trend was evident at the -0.033 MPa moisture potential ($P<0.10$).

Compaction had the most pronounced effect on soil water retention in 1985 (Table 4). Compaction reduced total water holding capacity at 0 MPa by 6.3% while water retention at -0.033 MPa increased 3.4% compared to noncompacted plots. This indicates compaction increased the percentage of fine pores at the expense of larger pores (Table 2). Swartz and Kardos (1963) observed a similar response to compaction.

The type of tine used in cultivation had a tendency to influence moisture retention at 0 and -0.010 MPa ($P<.10$). Hollow tine cultivation

Table 3. The effects of compaction, cultivation, and soil moisture during cultivation on moisture retention at 0, -0.010, -0.033, and -0.100 MPa in October, 1984.

Treatments	Moisture Potentials (-MPa) 0	0.010	0.033	0.100
	% Volumetric Water Content			
Noncompacted (NC)				
Check (Ck)	33.4	19.5	15.8	14.5
Compacted (CD)				
Check	32.1	19.6	16.0	14.8
Hollow Moist	34.1	21.5	16.7	15.3
Hollow Wet	33.3	20.6	16.1	14.9
Solid Moist	32.9	20.6	15.7	14.4
Solid Wet	33.1	22.8	17.4	16.2

Contrasts	Mean Squares			
NC-Ck vs CD-Ck	2.535 +	0.015	0.060	0.135
Tine Type (T)	1.333	1.267	0.083	0.120
Moisture (M)	0.213	1.267	0.963	1.470
T x M	0.750	7.208 *	4.083 +	3.630 *
CD-Ck vs Cultivation	3.553 *	7.280 *	0.486	0.323
Error	0.590	1.117	1.004	0.623

* and + significant at the .05 and .10 level, respectively.
LSD (0.05) (TxM) at -0.010 MPa =1.9 and -0.100 MPa =1.4

Table 4. The effects of compaction, cultivation, and soil moisture during cultivation on moisture retention at 0, -0.010, -0.033, and -0.100 MPa moisture in October, 1985.

Treatments	Moisture Potential (-MPa) 0	0.010	0.033	0.100
	% Volumetric Water Content			
Noncompacted (NC)				
Check (Ck)	34.4	18.9	15.2	14.0
Hollow Moist	35.2	19.5	16.0	14.7
Hollow Wet	35.2	19.8	16.2	15.0
Solid Moist	33.7	19.6	16.0	14.6
Solid Wet	34.7	19.8	16.1	14.9
Compacted (CD)				
Check	31.9	19.8	16.3	14.8
Hollow Moist	33.1	19.0	15.8	14.7
Hollow Wet	33.1	19.9	16.6	15.2
Solid Moist	31.9	20.0	16.4	15.1
Solid Wet	32.3	20.9	17.1	15.5
Comparisons	**Mean Squares**			
Compaction (C)	36.741 **	1.160	2.080 *	1.281
Tine Type (T)	5.900 +	1.602 +	0.327	0.135
Moisture (M)	0.844	1.707 +	1.127	0.735
C x T	0.000	1.307	0.667	0.375
C x M	0.120	0.602	0.427	0.042
T x M	0.700	0.007	0.007	0.007
C x T x M	0.120	0.015	0.000	0.007
NC-Ck vs Cultivation	0.308	1.442	1.734 +	1.734 +
CD-Ck vs Cultivation	1.233	0.048	0.113	0.193
Error	1.385	0.518	0.434	0.440

**, * and + significant at the .01, .05, and .10 level, respectively.

yielded 3.0% higher total water capacity (0 MPa) than solid tine cultivation. At -0.010 MPa solid tine cultivation resulted in 2.7% greater soil moisture retention than hollow tine cultivation across all treatments. Soil moisture during cultivation tended to influence moisture retention at -0.010 MPa with wet soil during cultivation increasing water retention 2.9% above moist soil cultivation treatments.

At -0.033 MPa the average cultivation effect tended to increase moisture retention 5.8% above the check in noncompacted soil (P=0.06). This effect was not apparent in compacted soil.

Soil Porosity

Pore size distribution is generally divided into two ranges, macropores and micropores. Macropores provide the main channels for infiltration and drainage of water and aeration (Hillel, 1982). Microporosity provides for the retention of water and solutes. Soil moisture retention data indicated cultivation affected soil porosity. Therefore the percent porosity, as determined by the pores drained within various water potential ranges, was examined to evaluate cultivation effects on pore size distribution. Moisture potential ranges of 0 to -0.001, -0.001 to -0.010, -0.010 to -0.100, and greater than -0.100 MPa (-0.10 MPa to oven dry at 105 C) were used. The range of 0 to -0.001 MPa was used to quantify the amount of very large pores created with cultivation i.e., tine holes. The range of -0.001 to -0.01 MPa was used to determine what effect cultivation had on the remaining macroporosity. Microporosity was divided into the final two ranges to measure any influence of cultivation on increasing the amount of finer pores.

Pore size distributions for 1984 are presented in Table 5. A tine effect significant at the 10% level was found with hollow tine coring resulting in a slightly greater amount of large pores than solid tine cultivation for the 0 to -0.001 MPa range. Porosity in the -0.001 to -0.010 MPa range was unaffected by treatment. Therefore, after one set of cultivation treatments macroporosity in the 0 to 7.6 cm soil zone was not appreciably altered with cultivation.

Microporosity, however, was significantly altered by treatment in 1984. The comparison of the control against the average cultivation effect in compacted soil showed cultivation increased the amount of

Table 5. The effects of compaction, cultivation, and soil moisture during cultivation on percent porosity within various moisture potential ranges in October, 1984.

	Moisture Potential Range (-MPa)			
Treatments	0-.001	.001-.010	.010-.100	> .100
	% Porosity			
Noncompacted (NC)				
Check (Ck)	3.2	10.7	5.0	14.5
Compacted (CD)				
Check	2.9	9.6	4.8	14.8
Hollow Moist	3.4	9.2	6.2	15.3
Hollow Wet	3.2	9.5	5.7	14.9
Solid Moist	2.8	9.5	6.2	14.4
Solid Wet	2.7	7.7	6.6	16.2
Comparisons	Mean Squares			
NC-Ck vs CD-Ck	0.135	1.927	0.042	0.135
Tine Type (T)	0.963 +	1.763	0.801	0.067
Moisture (M)	0.083	1.763	0.008	1.541
T x M	0.013	3.630	0.608	3.521 *
C-Ck vs Cultivation	0.043	1.014	4.320 *	0.368
Error	0.211	2.408	0.582	0.627

* and + denote significance at the .05 and .01 level, repectively.
LSD(0.05) (TxM) at > -0.100 MPa =1.4

pores drained in the -0.010 to -0.100 MPa range by 28.6%. A significant tine by moisture interaction was observed in the porosity range greater than -0.100 MPa. In this interaction solid tine cultivation under wet soil conditions resulted in a 12.5% increase in the percentage of pores when compared to solid tine cultivation under drier (moist) soil conditions. This moisture effect was not evident with hollow tine cultivation.

Pore size distributions for 1985 are shown in Table 6. In 1985 treatment effects on pores drained in the 0 to -0.001 MPa range were more pronounced. Compacted plots resulted in 13.1% lower porosity values compared to noncompacted plots. A highly significant tine effect was also found in this pore size range. Hollow tine cultivation yielded 25.8% greater porosity values than solid tine cultivation across all treatments. Highly significant cultivation effects were also found in this range. Cultivation in noncompacted and compacted soil increased porosity values 46.2 and 43.5% above the respective controls. Thus after 4 sets of cultivation treatments the percentage of very large pores increased with cultivation with hollow tine cultivation being the most effective in producing this response regardless of compaction or soil moisture levels at the time of cultivation.

In the -0.001 to -0.010 MPa range (remaining macroporosity) compaction significantly decreased percent porosity 18.8% below noncompacted plots. Cultivation also influenced porosity in this range when performed in noncompacted soil. Porosity was reduced 12.4% with cultivation when compared to the control. This effect was not apparent in compacted soil conditions. Thus after 2 years of cultivation macroporosity has been altered with cultivation. Cultivation,

Table 6. The effects of compaction, cultivation, and soil moisture during cultivation on percent porosity within various moisture potential ranges in October, 1985.

Treatments	Moisture Potential Range (-MPa) 0-.001	.001-.010	.010-.100	> .100
	% Porosity			
Noncompacted (NC)				
Check (Ck)	2.6	12.9	4.9	14.0
Hollow Moist	4.4	11.4	4.8	14.7
Hollow Wet	4.1	11.3	4.8	15.0
Solid Moist	3.1	11.0	5.1	14.6
Solid Wet	3.4	11.5	4.8	14.9
Compacted (CD)				
Check	2.3	9.7	5.0	14.8
Hollow Moist	3.6	10.4	4.4	14.6
Hollow Wet	3.5	9.7	4.7	15.2
Solid Moist	2.9	9.0	4.9	15.1
Solid Wet	3.0	8.4	5.3	15.5
Comparisons	**Mean Squares**			
Compaction (C)	1.408 **	34.992 **	0.000	1.083
Tine Type (T)	3.920 **	3.010	0.844 **	0.135
Moisture (M)	0.010	0.304	0.120	1.042
C x T	0.220	2.600	0.260	0.375
C x M	0.004	1.170	0.350 +	0.042
T x M	0.260	0.220	0.010	0.002
C x T x M	0.050	0.094	0.050	0.002
NC-Ck vs Cultivation	3.361 **	6.208 *	0.000	1.473 +
CD-Ck vs Cultivation	2.282 **	0.294	0.104	0.216
Error	0.157	1.362	0.097	0.447

**, * and + significant at the .01, .05, and .10 level, respectively.

particularly with hollow tines, increased the amount of very large voids. However, in noncompacted soil a loss of pores in the -0.001 to -0.010 MPa range coincided with the increase of very large voids in the 0 to -0.001 MPa range.

A highly significant tine effect was found in the -0.010 to -0.100 MPa range with solid tine cultivation resulting in a 6.4% increase over hollow tine cultivation across both levels of compaction and soil moisture. Also noted in this range was a compaction by moisture interaction ($P<.10$). This trend indicated that micropores in this range were found in greater quantity when cultivation in compacted soils was performed under wet soil conditons. This effect was not found in noncompacted soils suggesting soil moisture content during cultivation may be more of a concern in compacted soils.

The only effect on porosity in the range greater than -0.100 MPa was a trend ($P<0.09$) with cultivation in noncompacted soil increasing porosity 6.5% above the check.

Cultivation influenced soil porosity both positively and negatively. While the amount of larger pores between 0 and -0.001 MPa were increased with cultivation a decrease in the remaining macropores (-0.001 to -0.010 MPa) occurred with cultivation in noncompacted soil. Soil porosity data also show that hollow tine cultivation is more effective in increasing the amount of large pores between 0 and -0.001 MPa while solid tine cultivation is most effective in increasing the amount of finer pores between -0.010 and -0.100 MPa.

Field Water Infiltration Rate

Data and analysis for water infiltraton rates in September of 1984 are shown in Table 7. Interestingly, compaction had no significant effect on field infiltration rates. No significant differences were found due to the type of tine used in cultivation, although cultivation under wet conditions significantly reduced water infiltration rates by 38% when compared to cultivation under moist soil conditions.

Saturated Hydraulic Conductivity

Data and comparisons for 1984 water conductivity rates are presented in Table 7. Compaction had the only significant effect on conductivity in 1984 with the compacted check yielding a 50% lower water conductivity rate than the noncompacted check. No significant differences were observed between individual cultivation treatments.

Data and analysis for 1985 saturated water conductivity are presented in Table 8. In 1985 compaction resulted in a 42.7% reduction in water conductivity below the noncompacted plots. A significant reduction in conductivity due to cultivation was found in noncompacted soil. Cultivation reduced water conductivity 37.7% below the noncompacted check. A similar effect was apparent in compacted soil with cultivation decreasing conductivity 40.0% below the check. However, this effect was only significant at the 8.4% level. These data indicate cultivation has a negative effect on subsurface water flow most likely due to localized compaction (reduced pore size) at the lower end of the cultivation zone. Even though macroporosity can be increased with cultivation the continuity of these large voids at the bottom of the cultivation zone is most likely interrupted by localized areas of

Table 7. The effects of compaction, cultivation, and soil moisture during cultivation on field infiltration rates and saturated hydraulic conductivity in September and October, respectively, of 1984.

Treatments	Field Infiltration (Parameter, cm hr^{-1})	Saturated Conductivity (Parameter, cm hr^{-1})
Noncompacted (NC)		
Check (Ck)	3.0	4.8
Compacted (CD)		
Check	2.3	2.4
Hollow Moist	2.3	3.1
Hollow Wet	1.8	3.2
Solid Moist	2.5	3.1
Solid Wet	1.2	1.8
Comparisons	**Mean Squares**	
NC-Ck vs CD-Ck	0.602	8.640 *
Tine Type (T)	0.083	1.267
Moisture (M)	2.163 *	1.141
T x M	0.563	1.541
CD-Ck vs Cultivation	0.3841	0.308
Error	0.391	1.633

* significance at the .05 level.

Table 8. The effects of compaction, cultivation, and soil moisture during cultivation on saturated hydraulic conductivity in October, 1985.

Treatments	Saturated Hydraulic Conductivity
	cm hr^{-1}
Noncompacted (NC)	
Check (Ck)	5.1
Hollow Moist	3.6
Hollow Wet	3.3
Solid Moist	2.9
Solid Wet	2.9
Compacted (CD)	
Check	3.0
Hollow Moist	2.1
Hollow Wet	1.9
Solid Moist	2.1
Solid Wet	1.1
Comparisons	**Mean Squares**
Compaction (C)	16.725 **
Tine Type (T)	1.402
Moisture (M)	0.807
C x T	0.060
C x M	0.375
T X M	0.107
C x T x M	0.375
NC-Ck vs Cultivation	9.362 **
CD-Ck vs Cultivation	3.313 +
Error	0.994

** and + significant at the .01, and .10 level, respectively.

reduced pore size. Nelson and Baver (1940) observed this effect on percolation rates in soil cores prepared with various sand separates.

No differences could be attributed to individual cultivation methods. All cultivation treatments on compacted plots resulted in decreased hydraulic conductivity in 1985 when compared to 1984 while untreated plots increased or remained unchanged. It should be noted that the solid tine wet soil cultivation treatment had reached a conductivity rate (1.8 cm hr^{-1}) classed as moderately slow (Davidson, 1965) in 1984 and continued to decline in 1985 to 1.1 cm hr^{-1}.

The fact that cultivation effects were only found in 1985 suggest that the possible detrimental effects of cultivation (induced hardpan) require several treatment applications before any measurable effects develop. Therefore, long term study of these effects would be more meaningful.

Oxygen Diffusion Rate (ODR)

Due to the fact that uniform soil moisture was difficult to maintain in the field ODR measurements were obtained in the laboratory at moisture potentials of -0.002, -0.003, and-0.004 MPa. ODR readings were made at the 3.8 cm depth in 7.6 I.D. by 7.6 cm high cores.

A significant difference in ODR was found only at -0.003 MPa. Cultivation resulted in 35.6% lower ODR when compared to the compacted check plot. Although this reduction in ODR is large the reduced levels were not below values considered limiting to plant growth. However this data again indicates cultivation can have a negative effect on soil structure in the lower region of the cultivation zone. ODR decreases as soil density increases (Asady et al., 1985).

The fact that ODR is not limiting below the -0.003 MPa moisture potential suggests that reduced oxygen supply would not be of great concern in restricting root growth in this soil, particularly in the surface 7.6 cm. Moisture potentials on this site rarely remain at such high moisture potentials longer than 12 hours following heavy rainfall or irrigation.

Table 9. The effects of compaction, cultivation, and soil moisture during cultivation on ODR at -0.002, -0.003, and -0.004 MPa in October, 1984.

	Moisture Potential (-MPa)		
Treatments	0.002	0.003	0.004
		$gm \times 10^{-8}\ cm^{-2}\ min^{-1}$	
Noncompacted (NC)			
Check (Ck)	8.8	42.9	75.8
Compacted (CD)			
Check	4.5	47.5	83.1
Hollow Moist	3.2	30.6	80.2
Hollow Wet	3.6	32.5	77.9
Solid Moist	4.4	36.3	83.4
Solid Wet	3.5	23.0	73.9
Comparisons		Mean Squares	
NC-Ck vs C-Ck	27.74	29.48	80.67
Tine Type (T)	0.85	11.21	0.33
Moisture (M)	0.27	98.61	104.43
T x M	1.33	171.76	38.88
CD-Ck vs Cultivation	1.73	670.67 **	43.35
Error	9.15	67.38	61.77

** significant at the .01 level.

Penetrometer Readings

The applied force required to press the penetrometer cone into the soil is referred to as the cone index. Quantitative information on soil compactness can be obtained from cone index readings taken at desired depth intervals which yield plots of cone index curves. Areas under each cone index curve at 2.5 cm depth intervals were measured for all treatments to the 15 cm depth in 1984 and 1985 and are presented in Tables 10 and 11, respectively.

Compaction significantly increased areas under the curve (soil strength) at all depth zones in 1984 and 1985. In 1984, cultivation decreased soil strength in both compacted and noncompacted soil. However, the depth of this effect ended in the 7.5 to 10 cm zone in noncompacted soil while cultivation in compacted soil influenced penetration resistance as deep as the 10 to 12.5 cm zone. The type of tine used in cultivation influenced soil strength in the 2.5 to 5 and 5 to 7.5 cm depth zones in 1984. Solid tine cultivation was more effective than hollow tine cultivation in reducing soil strength in this zone. This response could be seen visually immediately following treatment. Solid tine treated plots showed considerably more surface disruption (heaving) than hollow tine coring indicating greater displacement or loosening of the soil.

In 1985 cultivation again reduced soil strength. However, cultivation effects in noncompacted soil were only significant in the 2.5 to 5.0 cm zone. Cultivation in compacted soil reduced soil strength only to the 7.5 to 10 cm depth zone. Interestingly, 1985 data suggest continued cultivation has a reduced ability to lower soil strength at

Table 10. The effects of compaction, cultivation, and soil moisture during cultivation on areas under cone index curves at 2.5 cm intervals taken September 3 and 5, 1984.

	Depth Intervals (cm)					
	0-2.5	2.5-5.0	5.0-7.5	7.5-10	10-12.5	12.5-15
Treatments	area (cm^2)					
Noncompacted (NC)						
Check (Ck)	0.431	1.230	1.810	2.298	2.735	3.091
Hollow Moist	0.396	1.092	1.465	1.896	2.557	3.085
Hollow Wet	0.385	1.063	1.402	1.758	2.367	2.948
Solid Moist	0.314	0.850	1.184	1.684	2.431	2.994
Solid Wet	0.350	0.971	1.293	1.695	2.396	2.999
Compacted (CD)						
Check	0.592	1.643	2.362	2.896	3.407	3.425
Hollow Moist	0.419	1.103	1.500	2.086	2.907	3.465
Hollow Wet	0.402	1.052	1.414	1.948	2.724	3.292
Solid Moist	0.355	0.943	1.362	2.011	2.844	3.454
Solid Wet	0.402	1.069	1.402	1.839	2.563	3.137
Comparisons	Mean Squares					
Compaction (C)	0.025 **	0.109 **	0.235 **	0.629 **	1.151 **	0.822 *
Tine Type (T)	0.013	0.085 *	0.109 *	0.079	0.039	0.016
Moisture (M)	0.001	0.010	0.000	0.072	0.178	0.145
C x T	0.001	0.013	0.022	0.003	0.006	0.006
C x M	0.000	0.000	0.003	0.013	0.022	0.048
T X M	0.005	0.040	0.033	0.005	0.001	0.000
C x T x M	0.000	0.000	0.001	0.013	0.024	0.031
NC-Ck vs Cult	0.012 *	0.133 **	0.539 **	0.700 **	0.213	0.017
CD-Ck vs Cult	0.094 **	0.868 **	2.131 **	2.054 **	1.008 **	0.018
Error	0.003	0.012	0.019	0.040	0.064	0.114

Cult denotes cultivation.
** and * significant at the .01, and .05 level, respectively.

Table 11. The effects of compaction, cultivation, and soil moisture during cultivation on areas under cone index curves at 2.5 cm intervals taken November 27, 1985.

	Depth Intervals (cm)					
	0-2.5	2.5-5.0	5.0-7.5	7.5-10	10-12.5	12.5-15
Treatments	area (cm^2)					
Noncompacted (NC)						
Check (Ck)	0.379	1.276	1.977	2.402	2.856	3.218
Hollow Moist	0.305	0.879	1.385	2.075	2.815	3.327
Hollow Wet	0.293	0.914	1.488	2.218	3.028	3.585
Solid Moist	0.328	1.069	1.839	2.568	3.172	3.585
Solid Wet	0.333	1.051	1.580	2.166	2.925	3.091
Compacted (CD)						
Check	0.672	2.178	3.350	3.919	4.275	4.482
Hollow Moist	0.402	1.264	2.126	3.057	3.838	4.269
Hollow Wet	0.362	1.143	1.982	2.930	3.735	4.195
Solid Moist	0.425	1.425	2.459	3.281	3.884	4.309
Solid Wet	0.534	1.701	2.701	3.522	4.183	4.505
Comparisons	Mean Squares					
Compaction (C)	0.172 **	1.909 **	5.674 **	8.364 **	7.864 **	7.360 **
Tine Type (T)	0.025 *	0.410 **	0.957 **	0.594	0.209	0.005
Moisture (M)	0.001	0.011	0.001	0.008	0.010	0.005
C x T	0.007	0.057	0.096	0.053	0.022	0.129
C x M	0.002	0.007	0.024	0.052	0.020	0.048
T X M	0.010	0.045	0.000	0.012	0.001	0.087
C x T x M	0.007	0.075	0.209	0.313	0.279	0.392
NC-Ck vs Cult	0.010	0.212 *	0.391	0.051	0.040	0.077
CD-Ck vs Cult	0.140 **	1.516 **	2.559 **	1.249 **	0.320	0.063
Error	0.005	0.034	0.094	0.153	0.165	0.194

Cult denotes cultivation.
** and * significant at the .01, and .05 level, respectively.

deeper regions, particularly in noncompacted soil. This could be a result of cultivation building soil strength at the lower regions of the cultivation zone. Petrovic (1979) demonstrated the compactive effect of hollow tine coring at the lower end of the cultivation zone.

Tine differences were reversed in 1985 with solid tine cultivation producing significantly greater soil strength than hollow tine cultivation in the 0 to 2.5, 2.5 to 5.0, and 5.0 to 7.5 cm depth zones. One reason for this reversal can be attributed to the time penetrometer readings were taken. Readings in 1984 were taken approximately 1 week following treatment while 1985 readings were taken approximately 15 weeks after the last cultivation treatment. During this extended period in 1985 two sets of compaction treatments were applied. Any soil loosening with solid tine cultivation most likely resettled by the time penetrometer readings were taken in 1985. Opposite tine effects in 1984 and 1985 suggest although solid tine cultivation can be very effective in initially loosening the soil surface this response may not be as long lived as hollow tine cultivation.

Rooting

Root samples taken in November 1985 (ten weeks following last cultivation) show compaction reduced total root weights by 12.7% when compared to noncompacted plots (Table 12). Root densities were reduced in both the 0 to 7.5 and 7.5 to 15 cm zones by compaction. Sills and Carrow (1983) observed total root weights and root weight in all soil zones declined with compaction for perennial ryegrass.

Cultivation in noncompacted soil reduced total root weight 15.6% compared to the check. Root density data show reductions in rooting due to cultivation occurred primarily in the 0 to 7.5 cm zone with cultivation reducing root density 16.2% below the check in noncompacted soil. This cultivation effect was not apparent in compacted soil.

Reasons for reduced surface rooting with cultivation can be attributed to removal and/or destruction during the cultivation operation. Interestingly, cultivation in compacted soil does not show this type of response. Cultivation may have a more positive effect in compacted soil than in noncompacted. Soil porosity data (Table 6) showed cultivation in both compacted and noncompacted soil increased the percentage of very large voids (0 to -0.001 MPa moisture potential range). However, cultivation in noncompacted soil decreased the percentage of the remaining macropores (-0.001 to -0.010 MPa range). Areas of penetrometer cone index curves demonstrated the degree to which soil strength was reduced with cultivation was greater in compacted soil than noncompacted soil (Table 11).

Table 12. The effects of compaction, cultivation, and soil moisture during cultivation on total root weight and root density in November, 1985.

Treatments	Total Root Weight	Root Density 0-7.5 cm	Root Density 7.5-15.0 cm
	mg dm^{-2}	mg dm^{-3}	
Noncompacted (NC)			
Check (Ck)	8100	930	130
Hollow Moist	6990	810	110
Hollow Wet	6610	750	120
Solid Moist	6600	750	120
Solid Wet	7140	800	140
Compacted (CD)			
Check	6240	740	84
Hollow Moist	5890	680	93
Hollow Wet	6940	800	110
Solid Moist	5550	630	96
Solid Wet	6340	740	95
Comparisons	**Mean Squares[a]**		
Compaction (C)	60.43 **	61020.3 *	5824.13 **
Tine Type (T)	2.37	5046.0	54.00
Moisture (M)	15.05	18704.2	580.17
C x T	4.38	3952.7	580.17
C x M	10.64	18928.2	6.00
T X M	1.64	3750.0	66.67
C x T x M	5.11	5890.7	280.17
NC-Ck vs Cultivation	38.24 *	57660.0 *	303.75
CD-Ck vs Cultivation	0.10	1288.1	522.15
Error	6.93	11263.0	171.74

** and * significant at the .01, and .05 level, respectively.
a-Total root weight mean squares adjusted x 10^{-5}.

Greenhouse Study 1

Root development was examined at eight locations within each core consisting of two regions (outer and center) surrounding the coring hole and within each region, four depth zones at 2.5 cm intervals. The center region was a 2.5 cm diameter core taken surrounding and concentric to the tine hole. The outer region was 7.6 cm in diameter surrounding the center region sample yielding a doughnut shaped sample. The outside edge of this outer region sample was 1.25 cm from the core wall to avoid edge effects.

Total root length of the entire core was not significantly affected 14 days following treatment with tines (Table 13). However, root length of the outer region was significantly reduced 11.0% by treatment with tines. Within this outer region root density decreased in the 0 to 2.5 cm and 2.5 to 5.0 cm depth zones by 11.6 and 12.0%, respectively, as a result of treatment with tines compared to the check (Table 14). Reduced root development in the region outside the coring hole may be a result of root injury incurred during treatment with tines. Considerable heaving of the soil surface can occur with cultivation. This disruption of the soil could damage roots and would be a concern in weakly rooted turf.

Root length of the center region of the core was not significantly altered by treatment except in the 5.0 to 7.5 cm zone where root density was increased 41.1% by treatment with tines (Table 15). Conversely, in the center region root density at the 7.5 to 10.0 cm zone ($P<.10$) decreased under treatment with tines. These responses show coring soil with either hollow of solid tines can increase root density within the tine hole while root development below the tine hole can be reduced.

Table 13. Cultivation effects on root length 14 days following treatment with tines for greenhouse study 1.

Treatments	Location		
	Entire Core	Outside Region	Center Region
		meters	
Check	51.55	41.67	9.88
Hollow	49.88	36.92	12.66
Solid	48.52	37.23	11.29
Comparisons		Mean Squares	
Check vs Tines	20.82	70.20 *	14.56
Hollow vs Solid	2.80	0.25	4.71
Error	16.16	6.81	5.34

* significance at .05 level.

Table 14. Cultivation effects on root density in various zones of the core outer region 14 days following treatment with tines for greenhouse study 1.

Treatments	Depth Zones (cm)			
	0-2.5	2.5-5.0	5.0-7.5	7.5-10.0
	km m^{-3}			
Check	1.64	1.21	0.74	0.46
Hollow	1.41	1.08	0.68	0.41
Solid	1.49	1.05	0.71	0.36
Comparisons	Mean Squares			
Check vs Tines	0.115 **	0.071 **	0.006	0.019
Hollow vs Solid	0.014	0.003	0.003	0.007
Error	0.008	0.006	0.005	0.013

** significance at the .01 level.

Table 15. Cultivation effects on root density in various zones of the core center region 14 days following treatment with tines for greenhouse study 1.

Treatments	Depth Zones (cm)			
	0-2.5	2.5-5.0	5.0-7.5	7.5-10.0
	km m^{-3}			
Check	2.75	2.40	1.57	1.01
Hollow	3.75	3.14	2.15	0.77
Solid	3.24	2.87	2.28	0.36
Comparisons	Mean Squares			
Check vs Tines	1.870	1.244	1.387 *	0.663 +
Hollow vs Solid	0.650	0.182	0.042	0.424
Error	0.733	0.461	0.201	0.146

* and + significance at the .05 and .10 level, respectively.

Greenhouse Study 2

In the second greenhouse study total root length of the entire core was not significantly affected 16 days following treatment with tines (Table 16). However, there was a tendency for the solid tine treatment to decrease total root length compared to the hollow treatment under moist soil conditions ($P<0.09$).

Treatment influences on root length in the outer region were less significant in this study. Under wet soil conditions treatment with both tines reduced root length ($P<0.08$) in the outer region 8.3% when compared to the check. Under drier (moist) soil conditions the solid tine treatment reduced root development 9.9% compared to the hollow tine treatment ($P<0.08$).

Root length of the center region was unaffected by treatment with tines. However, a significant moisture effect was unexpectedly found with wet soil yielding 10.6% greater root length than moist soil. To achieve appropriate soil moisture contents prior to treatment a 2 hour period was allowed for thorough rewetting of the soil in wet coring treatment cores. Another 2 hour span was required for treatment application. During this time of differing soil moisture, rooting in the moist (drier) soil may have been restricted due to moisture stress and/or greater mechanical impedance. Noting the lower root densities found within the outer region (Table 17) as compared to the center region (Table 18) the potential for greater moisture extraction may have resulted in a moisture gradient within the core with the center being drier than the outer region. This would be an explanation for no moisture effect in the outer region.

Two extra cores per replication, one at each moisture level, were

Table 16. Cultivation effects on root length 16 days following treatment with tines at two soil moisture conditions for greenhouse study 2.

Treatments		Location		
		Entire Core	Outside Region	Center Region
			meters	
Moist	Check	95.14	82.20	12.34
	Hollow	98.40	84.65	13.75
	Solid	88.94	76.29	12.65
Wet	Check	100.69	86.76	13.93
	Hollow	93.97	79.29	14.68
	Solid	93.91	79.69	14.22
Comparisons			Mean Squares	
	Moist vs Wet	24.75	2.67	11.166 *
Within Moist Soil				
	Check vs Tines	5.77	14.40	1.938
	Hollow vs Solid	179.08 +	139.86 +	2.420
Within Wet Soil				
	Check vs Tines	121.50	141.14 +	0.735
	Hollow vs Solid	0.01	0.32	0.414
	Error	52.65	38.70	2.331

* and + significance at .05 and .10 level, respectively

Table 17. Cultivation effects on root density in various zones of the core outer region 16 days following treatment with tines at two soil moisture conditions for greenhouse study 2.

Treatments		Depth Zones (cm) 0-2.5	2.5-5.0	5.0-7.5	7.5-10.0
		$km\ m^{-3}$			
Moist	Check	3.14	1.98	1.66	1.26
	Hollow	2.95	2.11	1.82	1.36
	Solid	2.65	2.10	1.58	1.09
Wet	Check	3.08	2.12	1.79	1.45
	Hollow	2.91	2.03	1.64	1.13
	Solid	2.77	2.11	1.64	1.23
Comparisons		Mean Squares			
	Moist vs Wet	0.000	0.004	0.000	0.007
Within Moist Soil					
	Check vs Tines	0.311 +	0.039	0.004	0.004
	Hollow vs Solid	0.171	0.000	0.120 +	0.143 *
Within Wet Soil					
	Check vs Tines	0.152	0.006	0.060	0.191 **
	Hollow vs Solid	0.041	0.014	0.000	0.020
	Error	0.075	0.042	0.032	0.020

**, * and + significance at the .01, .05 and .10 level, respectively

Table 18. Cultivation effects on root density in various zones of the core center region 16 days following treatment with tines at two soil moisture conditions for greenhouse study 2.

		Depth Zones (cm)			
Treatments		0-2.5	2.5-5.0	5.0-7.5	7.5-10.0
			km m^{-3}		
	Check	3.35	2.54	2.06	1.63
Moist	Hollow	3.98	3.31	1.96	1.40
	Solid	3.81	3.02	1.73	1.24
	Check	3.89	2.85	2.11	1.95
Wet	Hollow	3.93	3.58	2.43	1.44
	Solid	3.89	3.38	2.15	1.61
Comparisons			Mean Squares		
	Moist vs Wet	0.226	0.574	0.589	0.350 *
Within Moist Soil					
	Check vs Tines	0.796	1.058	0.123	0.246 +
	Hollow vs Solid	0.063	0.168	0.106	0.050
Within Wet Soil					
	Check vs Tines	0.001	1.054	0.083	0.482 *
	Hollow vs Solid	0.003	0.082	0.154	0.054
	Error	0.299	0.378	0.237	0.068

* and + significance at the .05 and .10 level, respectively

included to evaluate the extent of rooting at the time of treatment. Root samples (Table 19) taken at this time also showed the moisture effect with drier (moist) soil conditions resulting in 17.4% lower root length within the center region than wet soil conditions, significant at the 5.6% level. Within the center region root density was mainly influenced in the 2.5 to 5 cm depth zone with wet soil conditions yielding 36.9% greater root density (Table 20).

Breakdown of the outer region root density into four 2.5 cm depth intervals is presented in Table 17. The effect of treatment with tines in the upper two zones was less evident relative to the first greenhouse study. There was only a tendency ($P<0.06$) for treatment with tines to reduce root development in the 0 to 2.5 cm depth zone under moist soil conditions. Quite possibly better rooting prior to treatment provided resistance to physical injury suggested to cause reduced root development in the first study. Better rooting would inhibit the heaving (disruptive) action caused during tine penetration by holding the soil in place thereby reducing damage to roots. Initial root samples from the two extra cores were taken on the same day of treatment application to evaluate the degree of rooting prior to treatment. Initial counts indicate that sod had rooted to approximately the same degree before treatment in study 2 as had been achieved at the conclusion of study 1 (Tables 19-20 and 13-15).

A response not observed in the first greenhouse study, showed root density was significantly reduced in the 7.5 to 10.0 cm depth zone of the outer region by treatment with tines. In wet soil root density was lowered 18.6% by treatment with tines. In drier (moist) soil the solid tine treatment resulted in 19.9% lower root density than the hollow tine

Table 19. The effect of a 4 hour soil moisture differential prior to treatment on root length for greenhouse study 2.

Treatment	Location: Entire Core	Outer Region	Center Region
		meters	
Moist	43.23	37.38	5.85
Wet	49.12	42.04	7.08
Comparison		Mean Squares	
Moist vs Wet	69.50	43.52	3.026 +
Error	23.84	27.41	0.331

+ significance at .10 level.

Table 20. The effect of a 4 hour soil moisture differential prior to treatment on root density in various zones of the core center region for greenhouse study 2.

Treatments	Depth Zones (cm): 0-2.5	2.5-5.0	5.0-7.5	7.5-10.0
		$km\ m^{-3}$		
Moist	2.21	1.03	.77	.53
Wet	2.69	1.41	.84	.55
Comparison		Mean Squares		
Moist vs Wet	0.466	0.293 *	0.008	0.001
Error	0.103	0.028	0.013	0.002

* significance at the .05 level.

treatment.

Root densities of the center region at 2.5 cm depth intervals are shown in Table 18. Significant differences in root density were found only in the 7.5 to 10 cm depth zone. In this zone treatment with tines under wet soil conditions reduced root density 21.8% below the check. A similar trend was noted in drier (moist) soil ($P<0.08$). Reduced root development below the tine hole may be a result of physical injury to the roots or soil compaction incurred during tine penetration restricting subsequent root growth. Petrovic (1979) demonstrated the compactive effects of hollow tines and noted compaction below the tine hole was longer lasting than the sidewall compaction. Soil compaction (reduced pore size) in the lower region of the cultivation zone could inhibit root penetration due to increased mechanical resistance and/or aeration restriction. Model equations of Gerard et al. (1982) show that soil strength accounted for 64 and 65% of the variability in cotton seedling root growth. Another possible reason could be that root redevelopment after treatment has not yet reached this depth and therefore would only be a temporary effect.

These responses suggest although tine holes formed during cultivation can increase root development within the tine hole, rooting below the zone of tine penetration can be inhibited. Over a period of years one could postulate these root responses to cultivation practices would lead to a redistribution of the root system limiting roots to the upper part of the soil. It would be important in future studies to evaluate the longevity of the responses shown here.

Another point to be made about these two greenhouse studies involves the obvious root density gradient within the soil cores. In future studies it would be desirable to use larger diameter cores in order to avoid this gradient in root density which could possibly have an effect on root responses. It would also be important to account for such a condition when sampling for root distribution.

SUMMARY

It is evident that both compaction and cultivation effects have continued to develop through the 2 years of this field study. Interpretation of these results should take into account that the responses found in this short term study may be enhanced with long term treatment.

As one might expect, compaction resulted in pronounced detrimental effects on soil structure. While cultivation yielded positive effects on some soil structural properties, some undesirable responses to cultivation were found as well. By the end of this investigation hollow tine cultivation reduced soil density and increased aeration porosity while solid tine cultivation showed no advantage to hollow tine cultivation when compared in these measures.

Soil porosity measurements indicated cultivation increased the amount of very large voids drained between 0 and -0.001 MPa in the soil, with hollow tine cultivation being more effective than solid tine cultivation. Associated with this increase in large voids was a reduction of the remaining macropores drained between -0.001 and -0.010 MPa with cultivation in noncompacted soil, a phenomenon not observed in compacted soil. Solid tine cultivation resulted in a greater amount of micropores between -0.010 and -0.100 MPa compared to hollow tine cultivation regardless of soil compaction and moisture levels. Based on the earlier findings of Petrovic (1979) it is suggested that the increase in macroporosity occurs in the upper region of the cultivation zone, i.e. tine holes, while the decrease in remaining macroporosity in noncompacted soil and the increase in the amount of finer pores with solid tine usage resides at the lower end of the cultivation zone. The results of hydraulic conductivity and ODR measurements in this study support this conclusion. Conductivity rates dropped dramatically as a result of cultivation, particularily in noncompacted soil. This effect was not as consistent in compacted soil and supports the idea of the compactive effect of cultivation having less influence in compacted soil, at least short term.

Soil moisture content during cultivation initially affected responses to cultivation, especially solid tine cultivation. However, the influence of soil moisture after 4 cultivation treatments was apparently negligible on the soil utilized in this study.

Penetrometer data in 1985 suggest cultivation in noncompacted soil developed greater soil strength in the region below the cultivation zone when compared to 1984 data. Initially, solid tine cultivation was more effective in loosening the surface soil than hollow tine cultivation, however this effect was reversed by the end of the study.

Root sampling in November, 1985 found rooting declined with cultivation in noncompacted soil and had no effect on root mass in compacted soil. Greenhouse studies demonstrated short term root response to "cultivation" increased rooting within the soil immediately surrounding tine holes, however, rooting was consistently inhibited below the depth of tine penetration. Further studies are warranted to determine the potential of cultivation to enhance and/or limit root development within and below the cultivation zone.

Based on the bulk density, soil porosity and soil strength responses to solid tine cultivation this practice cannot be considered as effective as hollow tine cultivation in relieving soil surface compaction. However, solid tine cultivation can decrease surface soil strength and increase the amount of large pores within the zone of cultivation. With this in mind, solid tine cultivation could be seen as an effective tool for short term relief of surface compaction. It is cautioned that the long term effects of solid tine use on a frequent basis is still to be determined.

LIST OF REFERENCES

LIST OF REFERENCES

Agnew, M. L., and R. N. Carrow. 1985. Soil compaction and moisture stress preconditioning in Kentucky bluegrss. I. Soil aeration, water use and root responses. Agron. J. 77:872-878.

Akram, Mohd., and W. D. Kemper. 1979. Infiltration of soils as affected by the pressure and water content at the time of compaction. Soil Sci. Soc. Am. J. 43:1080-1086.

Alderfer, R. B. 1954. Effects of soil compaction on bluegrass turf. Pennsylvania State College Turfgrass Conf. 23:31-32.

Asady, G. H., A. J. M. Smucker, and M. W. Adams. 1985. Seedling test for the quantitative measurement of root tolerances to compacted soil. Crop Sci. 25:802-806.

Baver, L. D. 1938. Soil permeability in relation to non-capillary porostiy. Soil Sci. Soc. Am. Proc. 3:52-56.

Baver, L. D., W. H. Gardner, and W. R. Gardner. 1972. Soil Physics (4th edition). John Wiley & Sons, Inc., New York. 498pp.

Beard, J. B. 1973. Turfgrass: Science and Culture. Prentice-Hall. New Jersey. 658pp.

Byrne, T. G., W. B. Davis, L. J. Booker, and L. F. Werenfels. 1965. A further evaluation of the vertical mulching method of improving old greens. Calif. Turfgrass Culture. 15(2):9-11.

Carrow, R. N. 1980. Influence of soil compaction on three turfgrass species. Agron. J. 72:1038-1042.

Cordukes, W. E. 1968. Compaction and wear of turfgrasses. The Golf Superintendent. 36(8):20-24.

Davidson, D. T. 1965. Penetromenter measurements. In C. A. Black (ed.) Methods of Soil Analysis. Part I. Agronomy 9:472-484.

Engel, R. E. 1951. Some preliminary results from turf cultivation. Rutgers University 19th annual short course in turf management. pp.17-22.

Engel, R. E. 1953. Turf cultivation. Proc. of schools of soils, fertilization, and turf maintenance. Royal Canadian Golf Assoc. Green Sec. pp:12-13.

Engel, R. E., and R. B. Alderfer. 1967. The effect of cultivation, topdressing, lime, nitrogen and wetting agent on thatch development in 1/4 inch bentgrass turf over a ten-year period. New Jersey Agric. Exp. Station Bul. 818:32-45.

Engel, R. E. 1970. Thatch, cultivation and top-dressing of closely-cut turf. Proc. of the First Int. Turfgrass Res. Conf. pp.496-501.

Free, G. R., J. Lamb, Jr., and E. A. Carleton. 1947. Compactibilty of certain soils as related to organic matter and erosion. Agron. J. 39:1068-1076.

Gerard, C. J., P. Sexton, and G. Shaw. 1982. Physical factors influencing soil strength and root growth. Agron. J. 74:875-879.

Grable, A. R., and E. G. Siemer. 1968. Effects of bulk density, aggregate size and soil water suction on oxygen diffusion, redox potentials and elongation of corn roots. Soil Sci. Soc. Am. Proc. 32:180-186.

Harper, II, J. C. 1953. Irrigation, compaction and aeration of fairway turf. USGA J. and Turf Management. 6(4):27-31.

Harris, W. L. 1971. The soil compaction process. In K. K. Barnes, W. M. Carleton, H. M. Taylor, R. I. Throckmorton, and G. E. VandenBerg (Organizers). Compaction of Agricultural Soils. Am. Soc. Agr. Eng. St. Joseph, Michigan. pp 9-44.

Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press Inc. New York. 364 pp.

Hughes, T. D., J. F. Stone, W. W. Huffine and J. R. Gingrich. 1966. Effect of soil bulk density and soil water pressure on emergence of grass seedlings. Agron. J. 58:549-553.

Klute, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. In C. A. Black (ed.) Methods of Soil Analysis. Part I. Agronomy 9:210-221.

Lemon, E. R., and A. E. Erickson. 1952. The measurement of oxygen diffusion in the soil with a platinum microelectrode. Soil Sci. Soc. Am. Proc. 16:160-163.

Letey, J., L. H. Stolzy, N. Valoras, and T. E. Szuszkiewicz. 1962. Influence of soil oxygen on growth and mineral concentration of barley. Agron. J. 54:538-540.

Letey, J., L. H. Stolzy, O. R. Hunt, and V. B. Youngner. 1964. Growth and nutrient uptake of Newport bluegrass as affected by soil oxygen. Plant and Soil. 20:143-148.

Letey, J., W. C. Morgan, S. J. Richards, and N. Valoras. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. III. Effects on oxygen diffusion rate and root growth. Agron. J. 58:531-535.

Lutz, J. F. 1952. Mechanical impedance and plant growth. In B. T. Shaw (ed.) Soil Physical Conditons and Plant Growth. Agronomy. 2:43-72.

Madison, J. H. 1971. Principles of Turfgrass Culture. Van Nostrand Reinhold Co., New York. p.162.

Marthaler, H. P., W. Vogelsanger, F. Richard, and P. J. Wierenga. 1983. A pressure transducer for field tensiometers. Soil Sci. Soc. Am. J. 47:624-627.

Murray, J. J., and F. V. Juska. 1977. Effect of management practices on thatch accumulation, turf quality, and leaf spot damage in common Kentucky bluegrass. Agron. J. 69:365-369.

Nelson, W. R., and L. D. Baver. 1940. Movement of water through soils in relation to the nature of the pores. Proc. Soil Sci. Soc. Am. 5:69-76.

Newman, E. I. 1966. A method of estimating the total root length of root in a sample. J. Applied Ecol. 3:139-145.

O'Niel, K. J., and R. N. Carrow. 1982. Kentucky bluegrass growth and water use under different soil compaction and irrigation regimes. Agron. J. 74:933-936.

O'Niel, K. J., and R. N. Carrow. 1983. Perennial ryegrass growth, water use and soil aeration status under soil compaction. Agron. J. 75:177-180.

Petrovic, A. M. 1979. The effects of vertical operating hollow tine (VOHT) cultivation on turfgrass soil structure. Ph.D. Dissertation. Michigan State University. 86pp.

Proctor, R. R. 1933. Fundamental principles of soil compaction. Engin. News-Rec., III:Aug. 31.

Reaves, C. A., and M. L. Nichols. 1955. Surface soil reaction to pressure. Agric. Eng. 36:813-816,820.

Rickman, R. W., J. Letey, and L. H. Stolzy. 1966. Plant responses to oxygen supply and physical resistance in the root environment. Soil Sci. Soc. Am. Proc. 30:304-307.

Rimmer, D. L. 1979. Effects of increasing compaction on grass growth in colliery spoil. Sports Turf Res. Inst. J. 55:153-162.

Roberts, J. M. 1975. Some influences of cultivation on the soil and turfgrass. M. S. Thesis. Purdue University. 60pp.

Schmidt, R. E. 1980. Bentgrass growth in relation to soil properties of Typic Hapludalfs soil variously modified for a golf green. Proc. Third Int. Turfgrass Res. Conf. pp. 205-214.

Sills, M. J., and R. N. Carrow. 1982. Soil compaction effects on nitrogen use in tall fescue. J. Am. Soc. Hort. Sci. 107(5):934-937.

Sills, M. J., and R. N. Carrow. 1983. Turfgrass growth, N use and water use under soil compaction and N fertilization. Agron. J. 75:488-492.

Smucker, A. J. M., S. L. McBurney, and A. K. Srivastava. 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agron. J. 74:500-503.

Steele, R. G. D., and J. H. Torie. 1980. Principles and Procedures of Statistics. (2^{nd} edition). McGraw-Hill, Inc. New York. 633pp.

Swartz, W. E., and L. T. Kardos. 1963. Effects of compaction on physical properties of sand-soil-peat mixtures at various moisture contents. Agron. J. 55:7-10.

Tackett, J. L. and R. W. Pearson. 1964. Oxygen requirements of cotton seedling roots for penetration of compacted soil cores. Soil Sci. Soc. Am. Proc. 28:600-605.

Tanner, C. B., and C. P. Mamaril. 1959. Pasture soil compaction by animal traffic. Agron. J. 51:329-331.

Taylor, H. M., and H. R. Gardner. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. Soil Sci. 96:153-156.

Taylor, H. M., G. M. Roberson, and J. J. Parker, Jr. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102:18-22.

Thurman, P. C., and F. A. Pokorny. 1969. The relationship of several amended soils and compaction rates on vegetative growth, root development and cold resistance of "Tifgreen" bermudagrass. Am. Soc. Hort. Sci., J. 94:463-465.

Turgeon, A. J. 1980. Turfgrass Management. Reston Publ. Co., Reston, Virginia. 391pp.

Valoras, N., W. C. Morgan, and J. Letey. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. II. Effects on top growth, salinity, and minerals in the tissue. Agron. J. 58:528-531.

Veihmeyer, F. J., and A. H. Hendrickson. 1948. Soil density and root penetration. Soil Sci. 65:487-493.

Waddington, D. V., and J. H. Baker. 1965. Influence of soil aeration on the growth and chemical composition of three grass species. Agron. J. 57:253-258.

Waddington, D. V., T. L. Zimmerman, G. L. Shoop, L. T. Kardos, and J. M. Duich. 1974. Soil modification for turfgrass areas. Pennsylvania Agr. Exp. Sta. Progress Report No. 337. 96pp.

Watson, J. R., Jr. 1950. Irrigation and compaction on established fairway turf. USGA J. and Turf Management. 3(4):25-28.

Wiersum, L. K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil. 9:75-85.

Wilkinson, J. F., and D. T. Duff. 1972. Rooting of Poa annua L., Poa pratensis L., and Agrostis plasturis Huds. at three soil bulk densities. Agron. J. 64:66-68.