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THE EFFECTS OF VERTICAL OPERATING
HOLLOW TINE (VOHT) CULTIVATION
ON TURFGRASS SOIL STRUCTURE

presented by

Anthony Martin Petrovic

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Crop and Soil Sciences

P. E. Rieke
Major professor

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THE EFFECTS OF VERTICAL OPERATING HOLLOW TINE (VOHT) CULTIVATION ON TURFGRASS SOIL STRUCTURE

By

Anthony Martin Petrovic

A DISSERTATION

Submitted to
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ABSTRACT

THE EFFECTS OF VERTICAL OPERATING HOLLOW TINE
(VOHT) CULTIVATION ON TURFGRASS SOIL STRUCTURE

By

Anthony Martin Petrovic

A method of VOHT (vertical operating hollow tine) core cultivation for laboratory and greenhouse experiments was studied. The field VOHT coring unit mechanism of tine movement is periodic in nature. In a laboratory study it was found that increasing the rate of tine movement from 0.5 to 1270 mm/min only increased the pressure required to cause tine penetration a maximum of 0.43 kg/cm^2. From the results of a confined compaction test it was concluded that a small pressure increase as noted here would have a negligible effect on soil bulk density. A machine that operates at a constant set rate of movement, such as an Instron[R] universal testing machine, therefore, can be used for greenhouse and laboratory studies to simulate the field VOHT core cultivator.

To determine the effects of VOHT cultivation on soil structure, a method of obtaining bulk density *in situ* for a volume of soil as small as 1.25 x 1.25 x 2 mm was developed. The technique of X-ray transmission computed tomography (CT) scanning, an advanced tool used in diagnostic radiology, was studied. CT scanner analysis of samples of Metea fine sandy loam and samples of glass bead-air filled glass spheres that ranged in bulk density from 0.14 to 1.64 g/cm^3 revealed that a positive machine

response occurred with increasing density. The minimum effective spatial resolution was determined for materials that varied greatly in density (air to acrylic) and that only had a 1% difference in attenuation coefficients. These resolutions were found to be 1.25 x 1.25 x 2.4 mm and 6.4 x 6.4 x 2.4 mm, respectively. Artifacts can occur when the sample container size and composition is not standardized and if large stones and/or long straight holes or channels are present in the sample. Simple methods can be used to correct for such artifacts.

Having the technology to accurately measure spatial variation in bulk density *in situ* for a volume of soil as large as 500 x 500 x 10 mm to as small as 1.25 x 1.25 x 2 mm will aid researchers in the field of soil science immensely.

The effects of VOHT coring on bulk density of a Metea sandy loam soil was examined in laboratory and greenhouse studies. Under laboratory conditions it was found that VOHT coring caused a significant increase bulk density in the soil surrounding the coring hole. The maximum density occurred within 1 to 2 mm from the edge of the coring hole and decreased linearly away from the hole for a distance of 10 to 12 mm. Tine size had little effect on the maximum density, however, the larger tines increased the distance of soil away from the coring hole with a higher bulk density. Decreasing the soil moisture content at the time of VOHT coring caused a slight decrease in the maximum density as well as a decrease in the size of the zone of soil with larger bulk density. The relative degree of compaction caused by VOHT coring was greater in the soil below the coring hole than at the edge of hole.

The results from the greenhouse study indicated that VOHT coring caused a similar degree and pattern of compaction as noted previously. Soil at a higher initial bulk density did not show a large level of increased compaction as the lower density soil. After 93 days following VOHT coring, the walls of the coring holes had collapsed. Soil below the coring hole, however was still at a similar compaction level noted at 14 days.

In a 2-year field study maintained under putting green conditions, it was found that VOHT cultivation had no short term significant effects on oxygen diffusion rates, turfgrass quality and soil strength.

The potential for the long term development of a layer of highly compacted soil just below the depth of cultivation exists. VOHT coring can still, however help reduce surface soil compaction problems on established turfgrass.

To my
wife Renie and my parents
for their love, patience and understanding

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INTRODUCTION

Soil compaction is a major problem associated with high use recreational areas such as golf course putting greens. Extensive foot and vehicular traffic can result in an increased compaction and an associated reduction of water movement into the soil, in poorly aerated soil conditions, and in a high soil mechanical impedence of root growth. The overall turfgrass quality is usually lower under compacted soil conditions. In addition, maintenance requirements are substantially larger under compacted soil conditions.

Common practices used to alleviate surface compaction on established turfs are traffic control measures and cultivation. Types of cultivation include slicing, spiking, coring and deeper subaerification. Several forms of core cultivation are spoon, drum and vertical operation hollow tine (VOHT).

The overall effects of VOHT coring on reducing the level of surface compaction, however are not clearly understood. The design of the coring tines are such that the hole made in the soil by coring is substantially larger than the cylinder or core of soil removed. The soil surrounding the coring hole must therefore be compressed to compensate for this size difference.

Research on the effects of VOHT coring on soil structure has been 1) limited by natural soil variability under field condition, 2) somewhat limited by the lack of a suitable laboratory coring machine, and 3) to a large extent by the current soil physical analytical methodology.

The objectives of the investigations were to:

(1) devise a method to simulate the field VOHT coring operation for use in laboratory and greenhouse studies;

(2) develop an analytical technique that can measure soil bulk densities *in situ* for a volume of soil 2 mm or less;

(3) study the effects of VOHT cultivation on soil structure as influenced by tine size, soil moisture content, and initial degree of soil compaction.

CHAPTER I

A VERTICAL OPERATING HOLLOW TINE (VOHT) TURFGRASS CORE CULTIVATOR FOR LABORATORY AND GREENHOUSE STUDIES

ABSTRACT

The mechanism of tine movement for a field VOHT (vertical operating hollow tine) core cultivator is periodic in nature. A laboratory study was conducted to determine if the rate of tine penetration has an appreciable effect on the force needed for penetration. Increasing rate of tine movement was found to have a slight effect on increasing force and pressure of tine penetration. However, the increase in pressure was small and should have a negligible effect on soil parameters such as bulk density. The Instron universal testing machine, which can be operated at a set rate of movement was found to simulate the field VOHT core cultivator and can, therefore, be used for laboratory and greenhouse studies.

INTRODUCTON

Compaction is a major problem associated with high use recreational turfgrass areas such as athletic fields, parks and golf courses. Common methods used to combat soil compaction are soil modification with sand and/or other coarse aggregates, traffic control and cultivation (1). Core cultivation, in particular the vertical operating hollow tine (VOHT) method, is widely used on golf course putting greens. Little, if any, research has been published on the effects of VOHT core cultivation on soil structure and plant growth.

The field VOHT coring machine has an oscillating speed of tine movement. This presents a problem of duplication of the technique for research studies since such mechanisms are both difficult and costly to construct. Units that have a constant speed driving head, such as the Instron universal testing machine, are commonly found in agricultural engineering and civil engineering laboratories.

The objective tested in this research were to determine 1) the effects of tine movement speed on the force required to cause tine penetration into the soil and 2) if the Instron machine would simulate the field core cultivator for use in greenhouse and laboratory studies.

MATERIALS AND METHODS

The speed of tine movement of a VOHT coring machine, in this case a Ryan's Greensaire® aerifier model A-5, was measured during operation in the field. At an engine speed of 300 rpm, the crank-rod-tine assembly rotated 237 rpm. The total vertical tine displacement was 11.4 cm. The maximum velocity of 85,070 mm/min occurred at 90° of crank rotation.

An Instron universal testing machine, model TM (see Fig. I.1.), was used to study tine penetration force as a function of tine velocity under laboratory conditions. Velocities selected were 0.51, 5.1, 51, 254, 510 and 1270 mm/min. 1270 mm/min is the maximum attainable speed for this unit.

Force required to cause tine penetration was monitored on a load cell and was plotted against distance of tine penetration with a chart recorder. The soil used was an air dried surface Metea fine sandy loam (loamy, mixed, mesic Arenic Hapludalf) passed through a 1.00 mm sieve. This soil contained 73% sand, 18.6% silt and 8.4% clay, and 1.1% organic matter.

Aluminum cylinders, 7.36 cm I.D. by 12.7 cm long, were covered at one end with two layers of cheese cloth and filled with uncompacted soil. The initial bulk density was 1.30 g/cm^3. The packed cylinders were placed on 1 bar porous ceramic plates, saturated for 24 hours with tap water, and then equilibrated at a potential of 0.33 bar in pressure extraction containers for 3 days. The moisture content by weight ranged from 10 to 11%. Compaction was applied three times to the upper surface at a pressure of 2.8 bar. A hydraulic compacting frame, similar to that described by Tanabe and Murdock (7) was used for compacting. The bulk density following compaction was 1.55 g/cm^3.

The Instron machine, fitted with a 6.4 mm I.D. coring tine, was used to core 3 replicates at each of the 6 speeds (previously listed) to a depth of 7.6 cm. The tine size referred to was that of the manufacturer; however, the actual measured I.D. was 7.0 mm. Prior to the coring treatments, one sample handled in the manner described above was cored so as to fill the tine with soil. Subsequently, the tine contained soil from the previously cored sample thus simulating the natural sequence observed in the field.

The general shape of the tine consisted of 3 succeedingly larger truncated cones with the uppermost cone connected to a short cylinder. The external cone diameters each reached a maximum at 1.5, 50.6 and 73.6 mm above the tine tip. The external surface area (cm^2) of the tine exposed to the soil at 20, 40, 60 and 76 mm from the tip was calculated and used to convert force of penetration (kg) into pressure (1 bar = 0.98 kg/cm^2).

A completely random design was utilized in this study. Regression equations describing force of tine penetration as a function of rate of tine movement at 20, 40, 60 and 76 mm in the depth of penetration were developed on a Tektronics mini-computer, model 4050, that contained

Plot 50: statistics[R] software.

The compactability of this soil as related to the compaction (load) pressure was determined by a confined compression test. Acrylic cylinders, 5.1 cm I.D. by 7 cm long, were filled with soil to give an average initial bulk density of 1.45 g/cm^3 ± 0.01. Subsamples of soil were taken during packing on which the gravimetric moisture content was determined (dried at 105 C for > 24 hours). The air dry density was then converted to the oven dry equivalent. Each sample received a surface application of tap water to bring the moisture content to 11% by weight and then placed in a desiccator and sealed for 4 days. A weight loss of approximately 0.5% occurred during this period due to water evaporation into the atmosphere within the desiccator. Loading pressures of 0.70, 2.76 and 4.55 bar were used to compact samples by the procedure described previously. The change in bulk density was determined by measuring the decrease in the height component of the volume occupied by soil. Five replications of each of the pressure treatments were arranged in a completely random design.

RESULTS AND DISCUSSION

The effect of tine movement rate on force required to cause tine penetration is shown in Table I.1. Increasing the speed generally resulted in a slight increase in force of tine penetration at each depth. However, this effect was minimal at speeds of 50 mm/min or greater. It was estimated from the regression equations shown in Table I.1. that an increase in the speed of tine movement from 1270 mm/min to the maximum observed for the field unit (85,070 mm/min) would result in only a slight rise in force. The plots of rate verses force of penetration showed no abrupt decrease in force, indicating that shear failures were not induced by speeds in this range.

The shape of the coring tine, a truncated cone, is similar to cone-type penetrometers used to measure soil strength. The effect of the rate of penetrometer probe penetration on the resistance of soil to penetration has been found to be inconsistent. Gerard, et al. (5), Voorhees, et al. (8), and Waldron and Constantin (9) have observed an increase in penetration resistance with an increase in rate. However, others have found no effect (2,3) or a slight decrease (4).

Changing the speed of tine movement in this case from 0.5 to 1270 mm/min was found to change tine penetration pressure less than 1 order of magnitude (Fig. I.2.). Pressure differences of such a small degree would appear to have very little impact on bulk density. As seen in Table I.2., increasing the compacting pressure from 0.70 bar to 4.55 bar resulted in an increase in bulk density of only 8.7%. This would correspond to a 1.3% increase in density for each order of magnitude increase in compacting pressure. This finding was very consistent with that observed by Reaves and Nichols (6). They found that the bulk density of a Decatur silty clay loam soil increased 1.3 to 2.3% (depending on moisture content) per magnitude of increase in load pressure for the pressures ranging from 0.18 to 4.23 bar.

CONCLUSIONS

The rate of tine movement was found to have a small effect on the force (or pressure) needed to cause tine penetration into the soil. The oscillating rate of tine penetration observed in the field VOHT coring machine, therefore, should have a negligible effect on the bulk density of this soil. The Instron unit, which operates at a set constant rate of penetration would simulate the field VOHT cultivator and can be used in laboratory and greenhouse studies.

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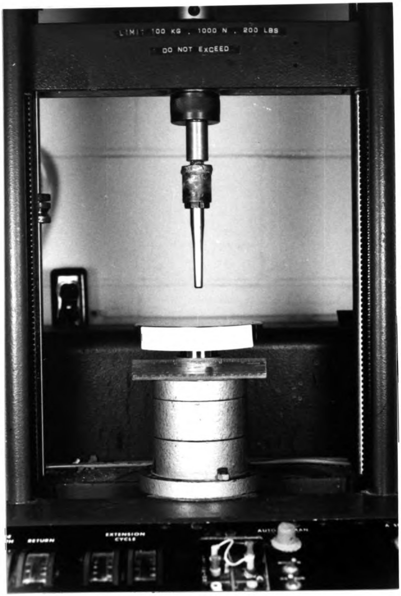

Fig. I.1. Photograph of Instron machine with 6.4 mm tine attached.

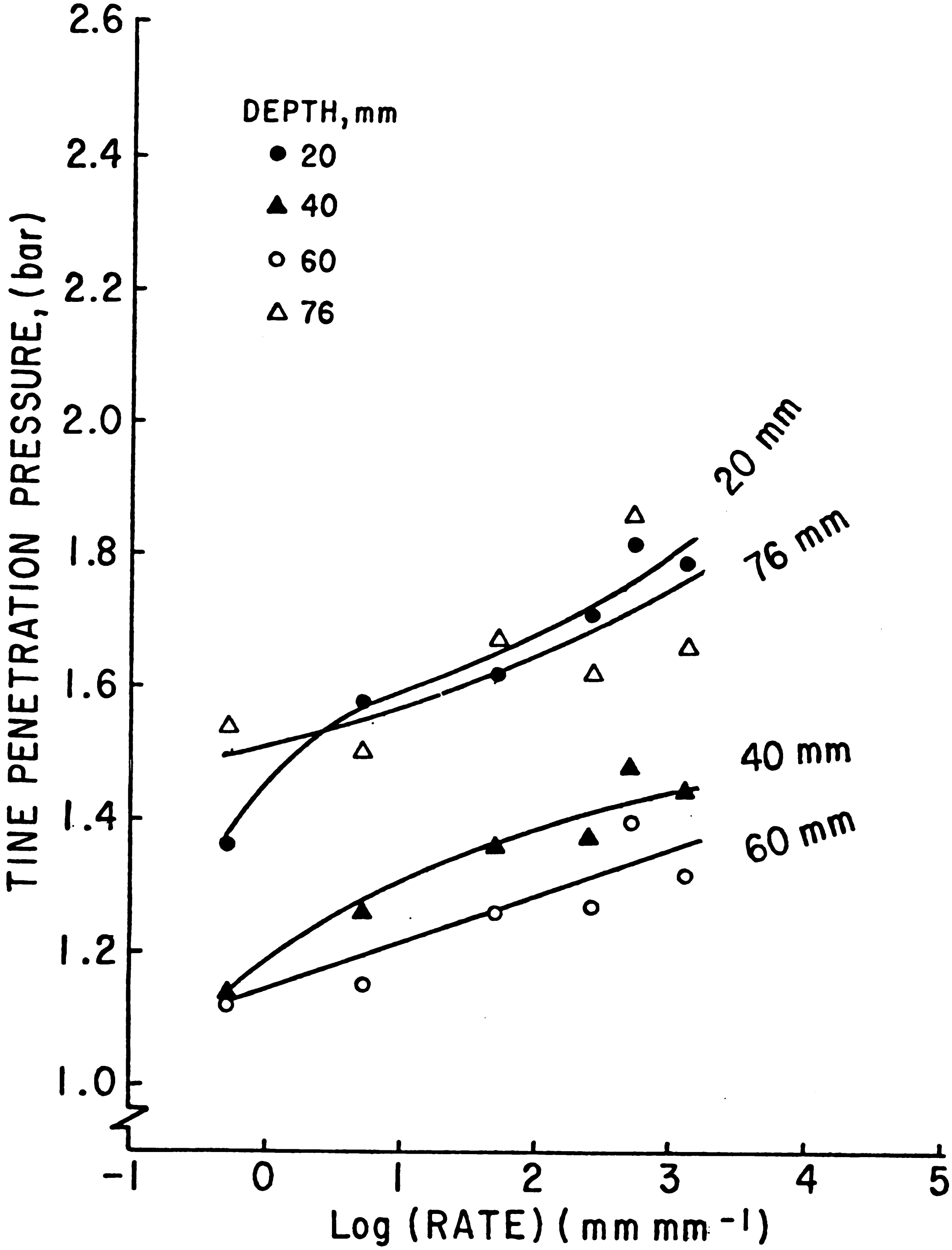

Fig. I.2. The effect of rate of penetration of a 6.4 mm tine on pressure required to cause tine movement at various depths below soil surface. The lines shown were developed from regression equations found in Table I.1.

Table I.1. Tine penetration force as a function of tine movement rate for a 6.4 mm tine.

Tine movement rate	Depth of tine penetration, mm			
	20	40	60	76
mm/min	------------------- kg -------------------			
0.51	6.0 a*	10.1 a	16.2 a	25.0 a
5.1	6.9 ab	11.2 ab	16.7 a	24.3 a
51	7.1 bc	12.1 bc	18.4 bc	27.2 a
254	7.5 bc	12.2 bc	18.5 bc	26.3 a
510	8.0 c	13.1 c	20.3 c	30.3 b
1270	7.9 c	12.7 c	19.2 c	27.0 a
85,070	10.9+	13.1+	21.7+	32.5+

*Values within columns followed by the same letter are not significantly different at the 5% level.

+Estimated values are from the following equations: 20 mm, $Y = 0.9293 \log X - 0.33309 (\log X)^2 + 0.067298 (\log X)^3 + 6.32$, $r^2 = .742^{**}$; 40 mm, $Y = 1.18996 \log X - 0.131865 (\log X)^2 + 10.41$, $r^2 = .748^{**}$; 60 mm, $Y = 1.08267 \log X + 16.34$, $r^2 = .637^{**}$; 76 mm, $Y = 0.82554 \log X + 0.158699 (\log X)^2 + 24.62$, $r^2 = .342^{*}$, where Y is force of tine penetration and X is tine movement rate.

Table I.2. The effect of compacting pressure on the bulk density of a Metea fine sandy loam soil.

Compacting pressure, bar	0+	0.7	2.76	4.55
	----------	---------- g/cm^3	----------	----------
	1.45	1.49 c*	1.54 b	1.62 a

*Values followed by the same letter are not significantly different at the 1% level.

+Initial bulk density.

CHAPTER II

DETERMINATION OF SOIL BULK DENSITY BY COMPUTED TOMOGRAPHIC (CT) SCANNING

ABSTRACT

Current soil bulk densitometric techniques have poor 3-dimensional spatial resolution. The X-ray transmission computed tomography (CT) scanner is on advanced tool in diagnostic radiology used to obtain a non-destructive cross-sectional representation of the human body with a spatial resolution of 2x2x2 mm or less. The machine response is known for materials with linear attenuation coefficients near water. Information on machine response at the upper limit of the measurement range where soil is located was determined.

Scanner analysis of soil and glass bead-air filled sphere samples, that varied in bulk density from 0.14 to 1.64 g/cm^3, revealed that a positive linear response occurred with increasing density. High and low contrast spatial resolution was found to be 1.25 x 1.25 x 2.4 mm and 6.4 x 6.4 x 2.4 mm, respectively.

Loss of data can occur as a result of certain machine artifacts, however, many of these can be avoided by relatively simple methods.

Thus, the CT scanner can be used for determinations of soil bulk density *in situ* with a fine 3-dimensional spatial resolution which offers promise to the field of soil science in the areas of compaction, soil management and cultivation research.

INTRODUCTION

Bulk density is widely used to characterize soil structure and compaction phenomena. Current methods of determining soil bulk density include the direct sampling by extraction of soil cores (17) or clods (1); in situ radiation methods such as single beam (25) and dual beam (5) gamma ray attenuation measurements, neutron scattering analysis (9); and to a lesser extent, by the analysis of shear- and compressional-wave propagation through column samples (22).

Studies involving modeling of soil mechanical processes (i.e., compaction, tillage and cultivation) in which fine 3-dimensional spatial resolution is required are limited by contemporary soil densitometry technology. Spatial resolution persists as the principal limitation of soil densitometry. Values obtained with cores or clods represent the gross average density of the sample and give little or no information concerning internal variation. Radiation techniques have improved on 1-dimensional resolution in the range of 0.5 mm (8). Resolution in orthogonal directions, however, is several centimeters. In addition, errors can occur in gamma ray densitometry if density within the beam path is not homogenous or if it fluctuates in a non-linear fashion (19).

The field of diagnostic radiology has been faced with a similar problem in attempting to obtain an accurate, non-destructive, low-radiation-dose, three-dimensional internal representations of the human body. Roentgen's discovery of the X-ray in 1895 and subsequent development of radioactive sensitive film and fluoroscopic screen resulted in the conventional X-ray shadowgram. Much information is lost, however, when a 3-dimensional object is superimposed on a 2-dimensional detector.

With recent advances in X-ray physics, detector technology and mathematical reconstruction theory, the X-ray Transmission Computer

Tomography (CT) scanner has emerged. The first usable CT scanner system was developed in]969 by Hounsfield (14) and units became available commercially in 1972. The advantage of the CT scanner over other radiographic processes is that a cross section of linear attenuation coefficients (μ) is obtained with a recordable radiation adsorption difference as low as 0.1% and a 2-dimensional resolution of 2 mm square or less. There are numerous extensive review articles on the physics, mathematics, and design of different CT scanners with extensive bibliographies such as Brooks and DiChiro (2,3) McCullough and Paine (18), Swindle and Barret (23) and Ter-Pogossian et al. (24).

Current CT scanner designs are focused on the medical imaging application of body tissues. Hence, instrument performance has been optimized for X-ray absorptions near that of water ($\mu \simeq 0.2\ cm^{-1}$) and of subjects of roughly circular cross section (ie. the cranium or abdomen). The typical μ for soils, however, lies near the upper limit of the measurement range of the instrument. Moreover, soil cores that are scanned in a vertical orientation would have a rectangular shaped cross-section. The objectives of the research reported here are to investigate the limitations, precision, linearity and resolution of CT scanner for determination of soil bulk density.

MATERIALS AND METHODS

Instrumentation

An American Science and Engineering, Inc. CT Scanner[R] housed at the Michigan State University Clinical Center was used for these studies. This scanner is a fourth generation type which employs a divergent X-ray fan beam that rotates inside the stationary ring of 600 scintillation detectors partially shown in Fig. II.1. The beam is collimated to form a 50° sector with a variable thickness of 2 to 10 mm. Bismuth germanate scintillation detectors are spaced at 0.6° intervals around the beam path. Either 6 or 12 second scan times may be selected. During a 12 second scan, each detector measures 1200 ray paths (projection) as the X-ray source rotates through the 90° in which that detector is illuminated.

A two-dimensional mapping of absorption values into a 512 x 512 element array [μ (x,y)] is reconstructed from the projection data acquired during a scan. The array is graphically displayed as an image on a high-resolution cathode ray tube monitor (see Figure II.4). As in most current commercial CT scanners, a reconstruction algorythm, called the convolution method of filtered-backprojection, generates the μ (x,y) (4,13). Image reconstruction utilizes a specialized extensive computer system to produce the resultant array in about 60 seconds.

Depending upon the selected mathematical scaling, the effective size of the 512 x 512 matrix of picture elements (pixels) comprising the image range from 0.25 mm square to 1.00 mm square area in the actual image plane. Hence, an individual pixel value can represent the absorption value of a volume element from 0.25 x 0.25 x 2 mm up to 1 x 1 x 10 mm. Objects up to 50 cm in diameter can be imaged.

As displayed, the brightness of a pixel is proportional to its numerical value [μ (x,y)]: the larger the μ(x,y) value, the brighter the pixel. To portray the array effectively, the operator interactively selects the mean value (window level) and the range (window width) of absorption values. Several software features assist the operator in printing out or plotting the numerical pixel values within interactively selected areas (known as a curson). The size and location of the cursor can be controlled. Average pixel values and standard deviations are available instantly by cursor manipulation.

The instrument output is not in the conventional μ units of cm^{-1}, but rather in a standardized number scale known as Hounsfield units (H). The linear scale is defined by two points: the absorption values of air and water being -1000 H and 0 H, respectively. Each H represents a 0.1% change in the absorption coefficient (μ).

Machine Response Studies

Response characteristics evaluated were as follows: linearity in response versus density changes for Hounsfield units ranging from -800 H to +800 H; spatial resolution; effective slice thickness or beam width; and beam hardening effect as influenced by sample size and density.

Samples of various proportions of glass beads and hollow glass spheres were used to study the linearity of scanner response with variations in bulk density. Aluminum cylinders 7.36 cm I.D. by 12.5 cm deep with a side wall thickness of 1.3 mm were filled with mixtures of glass beads 0.2 mm diameter (Ballontini^{R} impact beads, Potter Industries, Inc.) and glass bubbles 0.1 mm diameter (Microspheres^{R}, 3M, Inc.) to attain bulk densities of 0.04, 0.8, 1.0, 1.21, 1.32 and 1.55 g/cm^3. To facilitate uniform mixing, a small amount of distilled water was added to each mixture. Each sample was allowed to air dry, then scanned in 2 orientations and the results averaged.

Spatial resolution involves the ability to distinguish two objects contained in the zone of analysis. Objects that differ greatly in μ (high contrast) and objects that only vary slightly (low contrast) were used to determine the spatial resolving power of this scanner.

High-contrast spatial resolution was examined by a test procedure devised by an American Association of Physicists in Medicine (AAPM) for CT scanners (15). The test consists of scanning a 15 cm diameter acrylic cylinder containing a pattern of air-filled square holes with side dimensions of 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, and 2.50 mm. Distance between holes was the same as the hole width for a given size. The acrylic block was centered in a 21.5 cm diameter acrylic water tank.

Low contrast resolution was determined from a sample that contained holes that had a 1% difference in μ from the surrounding material. A 21.5 cm diameter acrylic cylinder, with holes filled with a fluid containing 50% glycerol to 50% propanol, was scanned.

Slice thickness or effective beam width is specified as the full width at half-maximum (FWHM) of the response across the slice orthogonal to the image plane (15). Again, the AAPM (15) recommendation for effective slice thickness determination was followed. A 0.5 mm thick by 25 mm long strand of aluminum positioned at 45° relative to the image plane was scanned. The resulting image depicts the effective beam profile. The FWHM points for 2 and 10 mm width beams were determined from this image.

Beam hardening or spectral shift is a phenomenon in which unequal filtration of the polychromatic X-ray beam occurs as the beam penetrates a sample. Photons of lower energy are more readily absorbed by photoelectric interactions as they pass thru material than higher energy photons. So as an X-ray beam passes through material it "hardens", becoming higher in effective energy. Attempts can be made physically and mathematically (7,16) to correct for this phenomenon, however, beam hardening artifacts do occur under certain conditions. The degree of beam hardening is related to the size, density and atomic number of the sample. Two acrylic cylinders with diameters of 21.5 cm and 30.5 cm were filled with water and used to demonstrate the effect of size on this type of artifact.

Zones of drastically changing density can also cause beam hardening artifacts. A sample of Metea fine sandy loam soil (refer to next section on soil preparation) was placed in a 7.36 cm I.D. by 12.5 cm long aluminum cylinder. A slightly tapered hole, 76 mm long with an upper diameter of 18 mm and bottom diameter of 16 mm, was made in the sample. The sample was scanned and then rescanned after refilling the hole with loosely packed soil. To determine the effects of stones on density of the adjacent soil, three stones varying in size were placed in aluminum cylinders containing water and glass beads were scanned.

Soil Studies

To evaluate CT scanner response to a soil, samples consisting of a Metea fine sandy loam (loamy, mixed mesic Arenic Hapludalf) were prepared and scanned. The first experiment involved scanning 12 soil samples of known bulk densities ranging from 1.28 to 1.64 g/cm^3 and obtaining the mean absorption value (H) over the sample cross section. The soil, at a moisture content of 6.0-7.5% by weight, was passed through a 1.00 mm sieve and packed into 3.2 cm I.D. by 4 cm high acrylic cylinders. Samples were oven dried at 105 C for 24 hours prior to scanning.

The effect of soil moisture content on the scanner response for a given dry bulk density was studied. Soil was placed in 7.36 cm I.D. x 12.7 cm long aluminum cylinders to a dry equivalent bulk density of 1.30 g/cm^3, saturated with tap water for 24 hours, and equilibrated to potentials of -9.5, -15, -35 and -100 cbar in pressure plate extraction equipment for 2 days. Three replicates of each moisture content were included.

The machine was calabrated for a 21.5 cm diameter acrylic water bath which set H for water at 0 $\pm$ 5. A water filled aluminum cylinder used in these studies also had a mean H value for water of 5 H. All samples were scanned with the X-ray source operated at 125 keV and 30 mA. The 12 second scanning mode was employed with a nominal 10 mm wide X-ray beam.

RESULTS AND DISCUSSION

Machine Response

Understanding the performance of the CT scanner in the range of Hounsfield units (H) greater than +400 has not been well documented (15). As seen in Fig. II.2., the CT scanner's response to increasing density in the glass bead-sphere samples was linear. Each unit rise in bulk density (mg/cm^3) corresponded to a 1.15 H increase. Scanner analysis of Metea soil samples (Fig. II.2.) also revealed that the machine responded in a linear fashion to changing density.

The standard deviations found in Table II.1. and regression equation in Fig. II.2. were used to explain the density resolving power of the CT scanner for the Metea soil. Standard deviations (σ) of the soil samples ranged from 9 to 50 H while the measurement of a uniform field of tap water yielded a σ of 3.5. Hence, the variation in the density and/or composition of these carefully prepared soil samples dominated over the variation of the measurement technique. A change in soil density of 3.8 mg/cm^3 would cause a 5 H change in absorption which is considered as the lower limit of density resolution with this machine. Improvements in density resolution can be made by employing longer scan times, higher energy X-ray beams, small sample size and wider slice thicknesses.

The slope of the linear regression lines shown in Fig. II.2. varied slightly between the glass bead-sphere and Metea soil studies. This probably occurred as a result of a difference in atomic composition between the two systems. When density and photon energy are held constant, μ is a function of the effective atomic number of the absorbing material (24).

Variation in volumetric moisture content (θ) in the Metea soil was detected by the CT scanner (see Fig. II.3.) A change in θ resulted in a corresponding linear change in H. It should be pointed out, however, that a large variation in μ occurred in these samples. Standard deviations ranged from 62 to 128 H in this case. It is apparent the further research is needed to clarify the capability of the CT scanner in determinating volumetric soil moisture content.

High contrast resolution, in this case air (-1000 H) to acrylic ($\simeq$ + 125 H), is shown in Fig. II.4. The CT scanner was able to clearly detect air-filled holes of 2.50, 2.00, 1.75, 1.50 and 1.25 mm in diameter. Holes of 1.00 were slightly visible but not seperated while 0.75 mm holes were not visible. Therefore, a 1.25 x 1.25 mm area in the image plane is considered the resolving power of this machine.

The ability to differentiate zones of material that have only a small difference in μ is vital in soil research. Fig. II.5. contains the CT image of the low contrast sample. A region as small as 6 mm can be detected for a difference in μ of 1% as shown here. Low contrast resolution is noise-limited since structures are hidden in the image grain.

The beam width determines the resolution in the direction perpendicular to the image plane. Fig. II.6. contains the beam profile plots at nominal settings of 2 and 10 mm. Effective beam width (slice thickness) is determined by the location of the full width at half maximum (FWHM) point on the beam profile and was found to be 2.4 and 7.6 mm for the 2 and 10 mm beams, respectively.

The beam hardening artifact can be a potential problem in soils research. The size of the sample has a small but pronounced effect on the image obtained. Water has an H value set at 0, however, the center value in the 21.5 and 30.5 cm diameter water baths were +9.6 and -17.2 H, respectively (Fig. II.7. A and B). The scanner can be calibrated for a particular size object which in this case was about a 25 cm diameter water bath.

In addition, a variation of 7.4 H occurred between the center and edge of the 30.5 cm sample (Fig. II.7 A and C). This difference is related to the length travelled by the X-ray beam through an absorber. The longer the path of travel the greater the likelihood that lower energy photons will be absorbed which will increase the effective energy of the beam.

It should be pointed out that in experiments involving comparisons of CT images, the size and composition of the sample container should be standardized to avoid an artifact of this nature. Errors introduced by the container can be readily seen by scanning it filled with water.

A zone of drastically changing density, such as an air-filled hole or a stone in soil, can cause the destruction of information due to beam hardening and mathematical anomalies. In the example where a long straight zone containing a large density gradient (Fig. II.8A), lines or streaks developed in the plane of symmetry at the density gradient interface. Filling the air-filled hole with loose unpacted soil eliminated the streaks (Fig. II.8B).

Fig. II.9. contains a series of CT images of different size stones in different media. It was found that only the large wedged shape stone (22 mm high by 15 mm at the base) had an appreciable negative effect on surrounding water beyond the interface region. The streaking was still evident when this stone was placed in the more dense glass beads (density similar to soil). (See Fig. II.9C.)

Many of the basic studies that have developed the fundamental concepts of compaction processes in soil have used less accurate indirect methods of analysis. These methods include strain gauge pressure cells (20,21), displacement of pins in a grid system (6,10,11), and the extraction of large soil cores (12) to obtain the gross average bulk density in a profile. It is likely that the addition of objects (strain gauges or pins) or the core sampling operation could have had some influence on the results of these studies.

SUMMARY

Studies were conducted to determine the limitations and precision of the CT scanner for soil bulk density determinations. The machine response was found to be linear with respect to increasing bulk density over a range of densities from 0.14 to 1.64 g/cm^3. High and low contrast spatial resolution were 1.25 x 1.25 x 2.4 mm and 6.4 x 6.4 x 2.4 mm, respectively. Information can be lost due to artifacts that occur when size and composition of the sample container varies, when large stones are present and when a long straight air filled hole or channel is in the sample.

Having the technology to accurately measure spatial variation in bulk density *in situ* for a volume of soil as large as 500 x 500 x 10 mm to as small as 1.25 x 1.25 x 2 mm will aid researchers in the field of soil science immensely.

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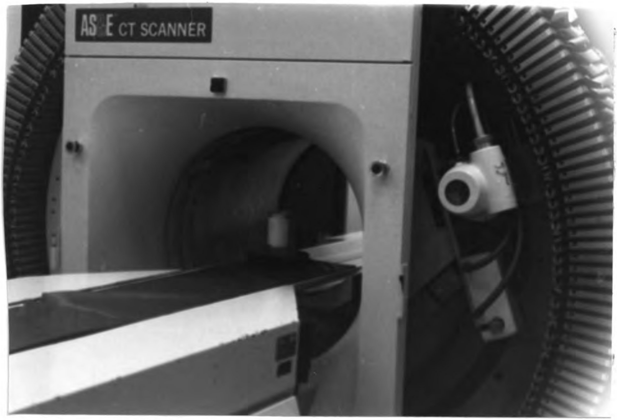


Fig. II.1. Photograph of CT scanner showing the exposed ring of detectors and X-ray source.

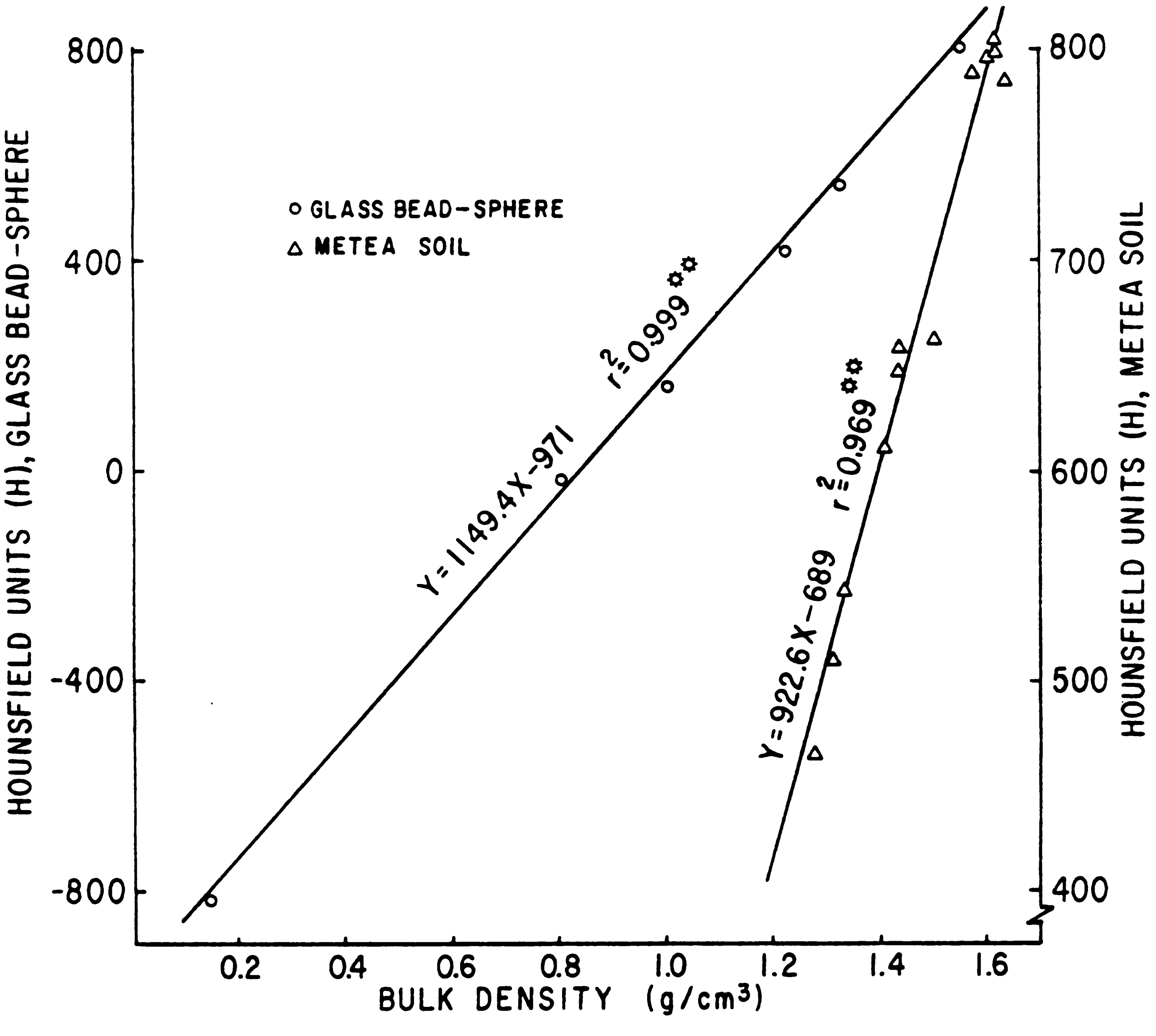


Fig. II.2. The influence of increasing bulk density of Metea soil and glass bead-sphere samples on Hounfield units.

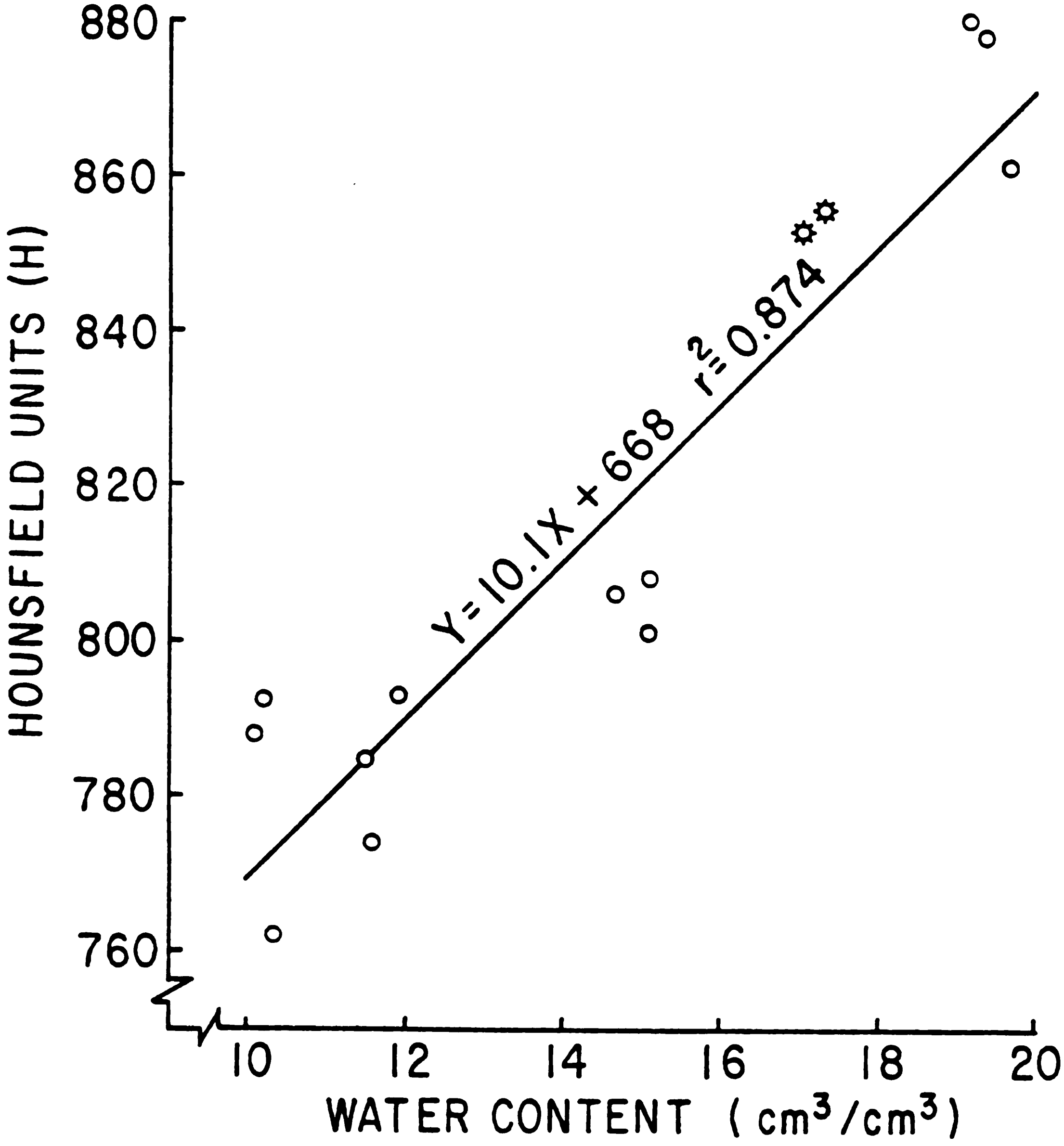
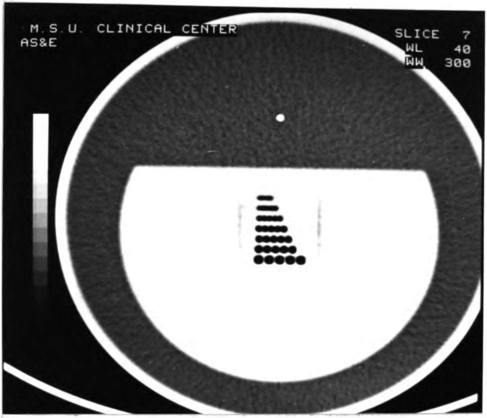
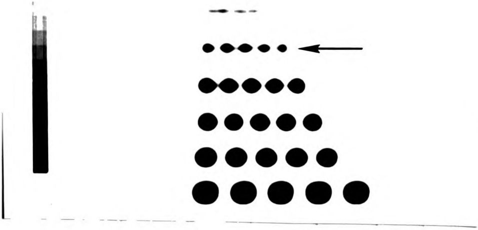


Fig. II.3. The effect of increasing volumetric water content on average Hounsfield units obtained from CT scanner analysis.



A



B

Fig. II.4. CT image of an acrylic cylinder (A) that contains a series of air-filled hole ranging in size from 2.50 to 0.75 mm in diameter. Note that the arrow in (B) locates the smallest visible holes (1.25 mm).

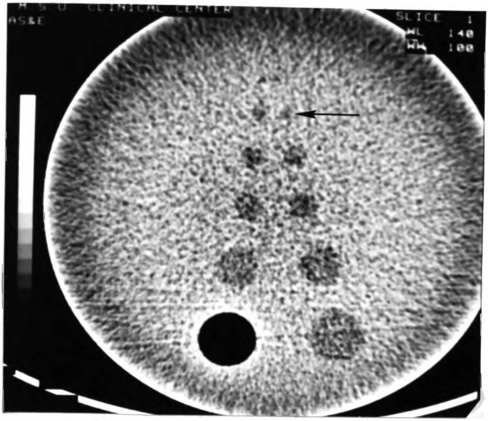


Fig. II.5. CT image of acrylic cylinder that contains various size holes filled with a glycerol: proponal mixture to illustrate low contrast spatial resolution. Note that the arrow locates the smallest visible hole (6.4 mm).

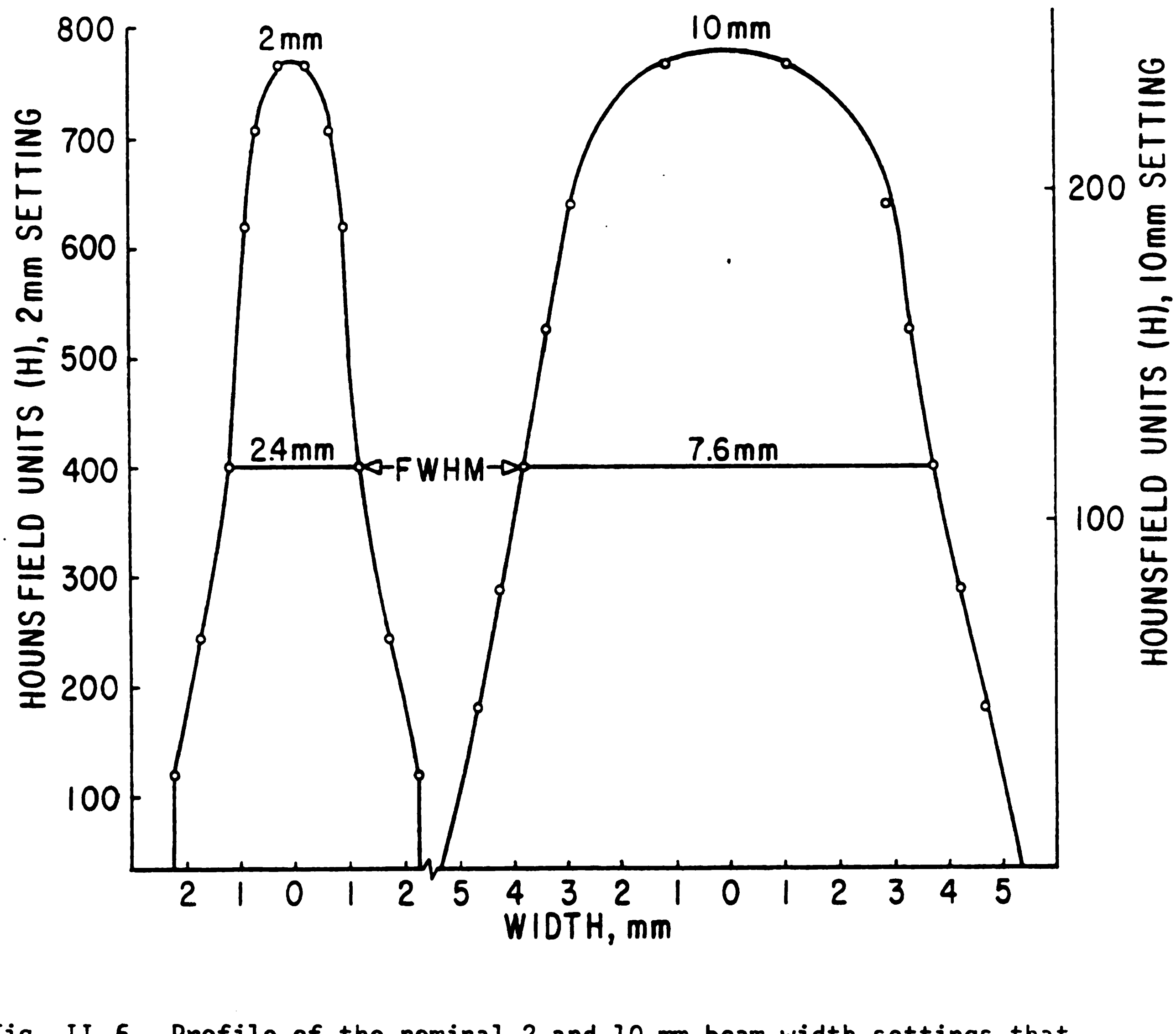


Fig. II.6. Profile of the nominal 2 and 10 mm beam width settings that contain the full width at half maximum (FWHM) points.

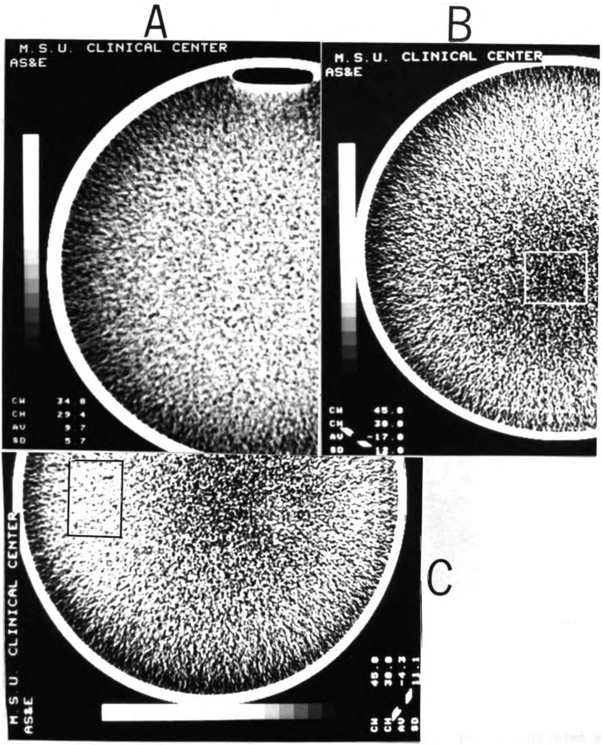


Fig. II.7. CT image of a 21.5 cm (A) and 30.5 cm (B and C) acrylic water baths.

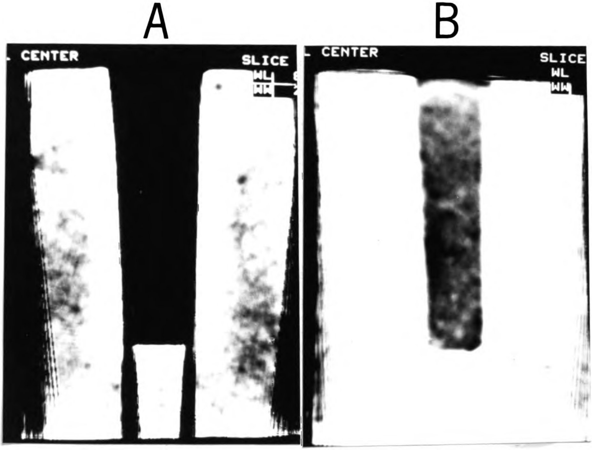


Fig. II.8. CT images of a Metea fine sandy loam soil sample containing a 76 mm long tapered hole (upper diameter of 18 mm, bottom diameter of 16 mm) scanned without (A) and with (B) loose soil placed back in the hole. Note artifacts streaks in (A) created as a result of beam hardening.

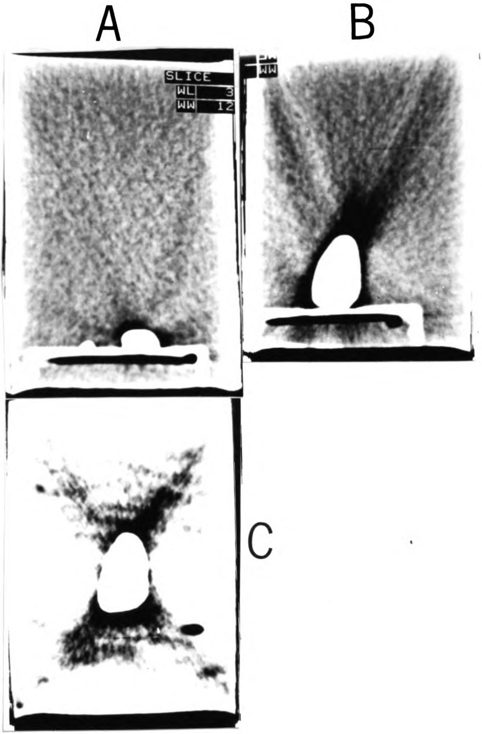


Fig. II.9. CT image of 3 stones of various sizes. Note that the small stones (A) have little effect on the surrounding water. The largest stone, however, caused great errors in the water (B) and in the glass beads (C) in the areas around the stone.

Table II.1. Mean and standard deviation of Hounsfield units obtained from computed tomographic (CT) analysis of Metea soil samples at various bulk densities.

Soil bulk density	Hounsfield units	
	Mean	Standard deviation
g/cm^3	H	
1.277	465	18.7
1.305	509	18.0
1.327	543	19.0
1.405	610	21.0
1.429	658	21.2
1.434	647	18.7
1.500	667	11.6
1.570	789	21.3
1.598	796	13.0
1.613	798	13.7
1.614	805	9.0
1.636	780	50.5
Tap water	0	3.5

CHAPTER III

SOIL COMPACTION - INDUCING EFFECT OF VERTICAL OPERATING HOLLOW TINE (VOHT) TURFGRASS CULTIVATION, A LABORATORY STUDY

ABSTRACT

The effects of vertical operating hollow tine (VOHT) turfgrass cultivation on soil bulk density, as influenced by tine size and soil moisture content, were examined under laboratory conditions. Samples of a Metea sandy loam surface soil were screened, compacted and equilibrated to moisture potentials of -9.5, -15 and -35 cbar. Tine sizes of 6.4, 9.5, 12.7 and 15.9 mm in diameter were used to core samples to a depth of 76 mm. A crosssectional array of soil bulk density values immediately following cultivation was obtained by X-ray transmission computed tomographic analysis.

In general, VOHT coring caused a large increase in bulk density in the soil surrounding the coring hole. The bulk density reached a maximum within 2 mm of the coring hole and decreased linearly away from the hole for a distance of 10 to 12 mm. Beyond this point there was no difference in bulk density between the cored and uncored samples.

Varying the tine size had little effect on the maximum density observed. The larger tines did, however, cause an increase of 3.3 mm in the distance away from the side of the coring holes that had higher bulk density.

Decreasing the soil moisture content was found to decrease the

maximum density and the thickness of the zone of soil with higher density at the side wall region of the coring hole for the 6.4 and 9.5 mm tines. This was not true for the 12.7 and 15.9 mm tines. The density of the soil below the coring hole was not influenced to a large degree by variations in tine size and/or moisture content.

The relative degree of increased soil bulk density (compaction) caused by VOHT cultivation was larger in the soil below the coring hole than at the side walls.

A bulk density gradient was very evident in the uncored samples. It is the assumption of many researchers that surface compacted disturbed samples like these have a uniform density profile. It is apparent that this may not be the case.

INTRODUCTION

Turfgrass cultivation involves mechanical methods of selectively tilling established turf without destroying the sod characteristics (1). VOHT (vertical operating hollow tine) core cultivation is primarily used on putting greens and tees to alleviate surface compaction, reduce thatch levels, and/or remove unwanted soil layers. However, evidence to support these uses is both limited and conflicting. Engel and Alderfer (4) found that during a 10 year field study under putting green conditions core cultivation had no significant effect on thatch reduction, water penetration, or overall turfgrass quality, and caused a slight increase in oxygen diffusion rate. Murray and Juska (8) observed, however, that coring reduced both thatch accumulation and leaf spot damage and improved the turf quality of common Kentucky bluegrass (*Poa pratensis* L.). Others have found that water infiltration rates were unaffected (2), reduced (13) or increased (16) by VOHT cultivation.

The degree to which a soil will compact is related to its moisture content. Reaves and Nichols (11) and Soehne (14) observed that soil bulk density increased in response to an applied pressure when the moisture content increased from air dry to the lower plastic limit (LPL). The LPL is defined as the minimum moisture content at which the soil particles are sufficiently lubricated so that an applied pressure will cause a perminant change in their size and shape.

The objectives of the research reported here were to determint if 1) VOHT coring causes compaction in the cultivation zone and 2) if the degree of soil compaction is related to tine size and soil moisture content at the time of coring.

MATERIALS AND METHODS

The Metea fine sandy loam soil (loamy, mixed, mesic Arenic Hapludalf) utilized in this investigation had the physical properties shown in Table III.1. The organic matter content of this soil was 1.1%. Following the procedures used by Tanabe and Murdoch (15), this soil was found to have saturated hydraulic conductivity of 0.13 cm/hour (after 24 hours with a 1 cm hydraulic head) at a bulk density of 1.62 g/cm^3.

Air dried soil was passed through a 1.00 mm sieve and packed into 7.36 cm I.D. by 12.7 cm long aluminum tubing. The initial bulk density was 1.29 g/cm^3. The samples were then equilibrated to a -33 cbar potential for 3 days and compacted on the upper surface with a hydraulic, compacting ram at a pressure of 2.8 bar. The density following compaction was 1.55 g/cm^3. The specific procedure used was similar to that of a previous study (10).

The samples were then placed on 1 bar porous ceramic plates, saturated for 1 day in tap water, and equilibrated to a potential of -9.5, -15 or -35 cbars for 2 days in pressure plate extractors. The Instron[R] machine (10) was used to core each sample at a vertical penetration rate of 51 mm/min to a depth of 76 mm. The force required to cause tine penetration was monitored during the operation.

Four sizes of Ryan's[R] Greensaire tines used were designated as 6.4, 9.5, 12.7 and 15.9 mm I.D. However, the actual inside diameters at the lower lip of the tines as measured were 7.0, 7.4, 9.8 and 12.7 mm, respectively. Thus the dimensions designated by the manufacturer are quite different from the actual inside diameters at the smallest point.

The 12 soil moisture potential-tine size treatments were replicated 3 times. Three uncored samples, equilibrated at -35 cbar potential, were included for comparison. Samples were oven dried for at least 24 hours at 105 C prior to density analyses. After equilibration, several samples at each moisture potential were sectioned at 2 cm intervals and moisture contents were determined. Moisture content was found to vary by less than 1% by weight within the soil columns.

Prior to the coring treatments, one sample handled in the manner described above was cored so as to fill the tine with soil. Subsequently, the tine contained soil from the previously cored sample thus better simulating the natural sequence observed in the field.

Bulk density for the region of soil surrounding the coring hole was determined by the x-ray transmission computed tomography (CT) scanning technique (9). Loose oven dried soil was lightly packed into the coring holes to avoid artifacts (9) at the bottom of the samples. The poly-cromatic X-ray beam generated was at a photon energy of 125 keV at 30 mA fo

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for a 12 second scan.

Each sample was positioned so that the 4 mm wide x-ray beam vertically bisected the coring hole (see Fig. III.1.). Raw data was obtained at various points adjacent to the hole left after coring. Eight horizontal rectangular sections from the center of the sample 30 mm wide, were taken from the following intervals below the soil surface: 0-8, 10-18, 20-28, 30-38, 40-48, 50-58, 60-68 and 70-73 mm. Vertical variation within each interval was small thus the data were averaged in the vertical direction.

Five vertical sections of data, 2 mm wide by 12 mm long, were obtained below the coring hole. Fig. III.1. shows the diagram of the zones selected for data analysis. The vertical sections as seen in Fig. III.1. referred to the following location: a, the center of the coring hole; b, mid point between a and edge of coring hole (c); and d, approximately midway between c and the outer edge of soil affected by the coring operation (e). The distance between these sections varied depending on tine size. It was found that the raw data only varied slightly in the horizontal direction (2 mm) of these sections. The data were therefore averaged horizontally over this region.

The output from the CT scanner is in Hounsfield units. Based on the results of a previous study (9), in which 12 samples of this soil at bulk densities ranging from 1.28 to 1.64 g/cm^3 were scanned, the following equation was used to convert Hounsfield units into bulk density:

$$Y = 0.00108X + 0.747 \qquad r^2 = 0.969^{**} \qquad [1]$$

where Y is bulk density and X is Hounsfield units.

A comparison of the density plots between uncored and cored samples revealed that a distance of 10 to 12 mm away the coring hole was affected by VOHT coring. Multiple regression equations were developed from data obtained in the horizontal and vertical section described above. A Tektronic[R] minicomputer, model 4050, with Plot 50: Statistic[R] software, using a forward model selection process, generated the equations and corresponding statistical analyses.

RESULTS AND DISCUSSION

Density Equations

Equations developed to describe density in the cultivation zone were divided into two regions. For the horizontal sections of soil (referred to as the side wall zone), density was a function of per cent soil moisture by weight (X_1), force of tine penetration in kg (X_2), and horizontal distance away from the edge of the coring hole in mm (X_3). Two general forms of equations found were:

$$Y = aX_1 + bX_2 + cX_3 + d \qquad [2]$$

$$Y = eX_1 + fX_2 + g \ln X_3 + h \qquad [3]$$

The coefficients and the coefficients of determination (R^2) for the side wall zone equations are shown in Table III.2.

Soil density in the vertical sections below the coring hole was found to conform to the following general equation:

$$Y = aX_1 + bX_2 + cX_3 + dX_3^2 + eX_3^3 + fX_3^4 + gX_3^5 + hX_3^6 + i \qquad [4]$$

where Y is bulk density, X_1 is percent soil moisture by weight, X_2 is the average force of tine penetration caused by the lower lip of the tine in kg and X_3 is the vertical distance below the bottom of the coring hole in mm. An exception to this equation occurred for the 6.4 mm tine at 3.6 and 6.6 mm distances away from the edge of the coring hole

(refer to vertical sections d and e in Fig. III.1.). In this case, density followed the equation:

$$Y = aX_1 + bX_2 + c\ \ln(X_3 + 1) + i \qquad [5]$$

Table III.3. contains the coefficients and the coefficients of determination (R^2) for these equations.

The equation describing density within the uncored soil was

$$Y = 0.0015X_1 - 0.0076X_2 - 0.00274X_2^2 + 0.000318X_2^3 + 1.6311$$
$$(R^2 = .700^{**}) \qquad [6]$$

where Y is bulk density, X_1 is the horizontal distance away from the center of the sample in mm and X_2 is the vertical distance below the soil surface in cm.

The regression coefficients shown in Tables III.2 and III.3. contained enough significant figures to estimate bulk density to the third decimal place (mg/cm^3).

Bulk Density Isograms

The effects of VOHT cultivation on soil bulk density are shown in Figs. III.3 through III.4. Equations [2] through [5], with coefficients found in Tables III.2 and III.3 and parameters listed in Table III.4 were used to develop the isograms. The parameters used in these equations were soil moisture content (X_1), force of tine penetration (X_2) and distance away from coring hole (X_3). Each figure contains a diagram of the external surface of the tine which would correspond to the hole remaining following cultivation. Points were joined by smooth curves. Fig. III.2 contains density plots for the uncored soils.

In the side wall zone, the lines of equal density generally were contoured parallel to the coring hole. Exceptions occurred near the cylinderical areas of the hole (upper 1 to 2 cm) for the 9.5, 12.7, and

15.9 mm tines. Density was observed to decrease linearly away from the hole in a horizontal direction for the first cm. Beyond this point density was comparable to that of the uncored soil.

Dexter and Tanner (3) studied the effects of vertical penetration of a 14.3 mm thick rectangular blade into a moist loamy sand. They observed a very similar pattern of equal lines of percent volumetric compression of this soil which conformed to the shape of the blade. In addition, they noted that the amount of compression decreased in a linear fashion with distance away from the blade. Gill (6) also found that compaction, as measured by soil displacement, decreased linearly away from the depression made in the soil by wedge-shaped tools.

The lines of equal density in the zone of soil below the lower lip and the bottom of the tine revealed that two areas of compaction occurred during VOHT coring. The first was region normal to the surface of the lower lip of the tine in which the lines were arranged in a bulb or arch-like pattern. The second area was located below the bottom of the tine from the edge to the center point of the tine. In this case the equal density lines were parallel to the bottom edge of the hole. Studies involving stress distribution caused by blunt-shaped probes (5,11) have shown that lines of equal stress conform to these general types of configurations. The 9.5 mm tine caused a slight variation in the equal density for the region below the coring hole in that the greatest density occurred midway between the edge of the tine and the center of the hole. (location b in Fig. III.1.)

The soil moisture content at the time of cultivation was found to significantly affect density in the side wall region for 6.4 and 9.5 mm tines (coefficients a and e in Table III.2.). In each case, the maximum density occurred at the LPL and became slightly smaller with drier soil conditions. This effect of moisture content on the compactability of a soil has been observed by others (11,14). Soil moisture content did not, however, consistently influence density in the soil below the coring hole (coefficient a in Table III.3.).

Varying the tine size had little effect on the magnitude of density observed. Tine size did, however, influence the area of soil that had a high bulk density. As stated earlier, this soil had a low saturated hydraulic conductivity (0.13 cm/hr) at a bulk density of 1.62 g/cm^3. A density of 1.62 g/cm^3, therefore, was set as a base above which density could severely restrict saturated water flow.

In the side wall region, increasing the tine size from 9.5 to 15.9 mm caused the zone of soil with density of $\geq$ 1.62 g/cm^{-3} to expand from 6 to 9.3 mm in length away from the hole (at 10.9% moisture content). In the area of soil below the coring hole this zone ($\geq$ 1.62 g/cm^3) ranged from 9 to 12 mm and was independent of the tine size and the soil moisture content.

In general, the region of soil below the coring hole had a slightly larger maximum density and a wider zone of density $\geq$ 1.62 g/cm^3 than the side wall area. When compared to the same locations in the uncored soil, the maximum densities were 9% higher in the side wall area and 17% higher below the hole than in the uncored soil.

The difference in magnitude of compaction between the side region and the region below the coring hole could be explained in part by the density gradient observed in the uncored soil (Fig. III.2). Reaves and Nichols (11) found that increasing the density of a soil a given amount at a specific load pressure is proportional to the degree the soil is already compacted.

It is interesting to note the density gradient that was present in the uncored soil (Fig. III.2). In this case, a pressure was applied to the upper surface of the sample. The result was that compaction, as indicated by higher bulk density, occurred not only at the upper surface but also at the sides and at the bottom of the container. Numerous studies in the past have examined compaction effects on soil physical properties and/or on plant growth in which surface compaction has been applied to disturbed confined samples. It is apparent that a compaction gradient similar to the one observed here could have developed and may have had a significant effect on the results of these studies.

Generalized Discussion

The hole remaining after coring is substantially larger than the core of soil removed. Thus it is not surprising that VOHT coring caused some compaction in the cultivation zone as observed in this study.

The weight of soil removed during VOHT coring was used to calculate the overall reduction in bulk density for the entire sample of soil (see Table III.5). The field VOHT coring machine has a normal tine spacing of 51 mm. This would represent on the average an area of 51 x 51 mm for each coring tine. Extrapolating the data in Table III.5 to the field tine spacing for a similar sample depth (105 mm) and coring depth (76 mm), VOHT coring would cause an overall reduction in bulk density of 1.3, 1.1, 2.0 and 3.4% for the 6.4, 9.5, 12.7 and 15.9 mm tines, respectively. The difference observed here is related to the I.D. of the tine at the lower lip which corresponds to the diameter of the core of soil removed.

As shown here, VOHT cultivation caused a maximum increase of 9 to 17% in bulk density for the soil adjacent (sidewall and below) to the coring hole. Thus, even though an overall reduction in bulk density (or increase in total porosity) for this soil would occur following VOHT coring, the net initial effect on water flow, aeration and overall turfgrass quality may be negligible due to the increased compaction in the zone of soil surrounding the coring hole.

It should be emphasized that the results found here only reflect a single cultivation treatment. Repeated coring to the same depth over a period of years could lead to the development of a highly compacted layer of soil just below the depth of cultivation. This would be similar to the plow sole formation observed in other agricultural operations.

There are conditions, however, under which improvements in the overall soil physical condition in the rooting zone would be expected to occur following core cultivation. In general, an area that contains an undesirable layer (or layers) within the depth of cultivation would show a positive response to VOHT coring. This layer may be either a zone of highly compacted soil or material that differs widely in texture or composition from the surrounding soil mass.

To a large degree, these conditions may help explain the lack of response observed by others. The field test area in the Engel and Alderfer (4) study involved an uncompacted Nixon loam soil that had a naturally high water infiltration rate (WIR).

Byrne et. al. (2) found that holes 2.5 cm in diameter by 15 cm deep, back filled with a coarse top soil mixture, resulted in an increase in WIR, whereas VOHT coring to a more shallow depth had no effect. In the case (13) where WIR was reduced following VOHT coring a small increase in bulk density in the 5 cm below the coring hole was reported. This would suggest that the compaction inducing effect of VOHT coring resulted in the lower WIR he observed.

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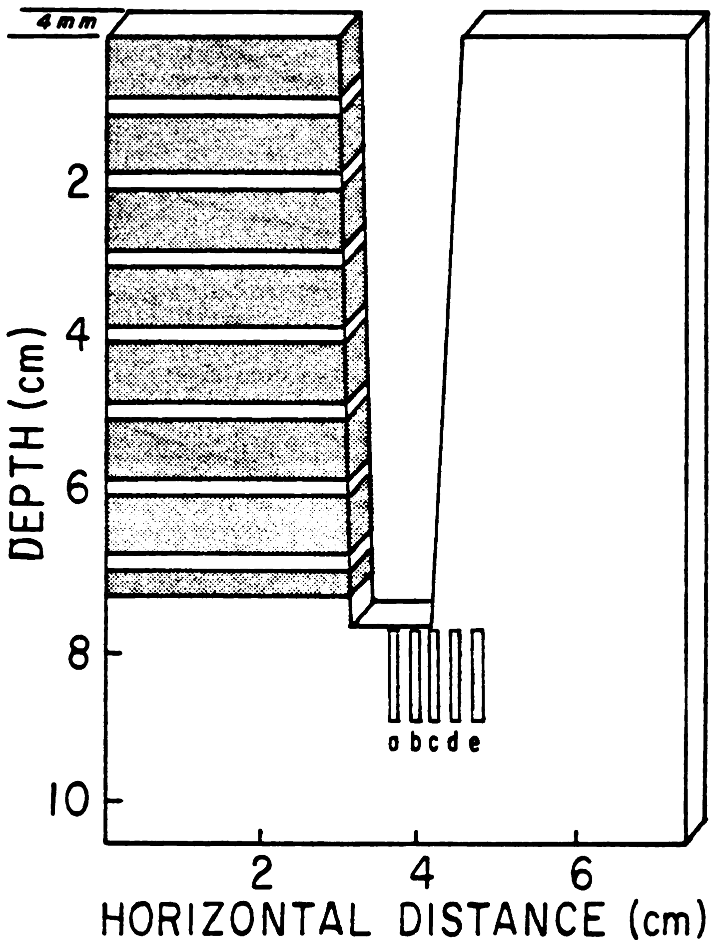

Fig. III.1. Diagram of cross-section obtained from the CT scanner. Shaded and lettered areas represent the locations of density analysis.

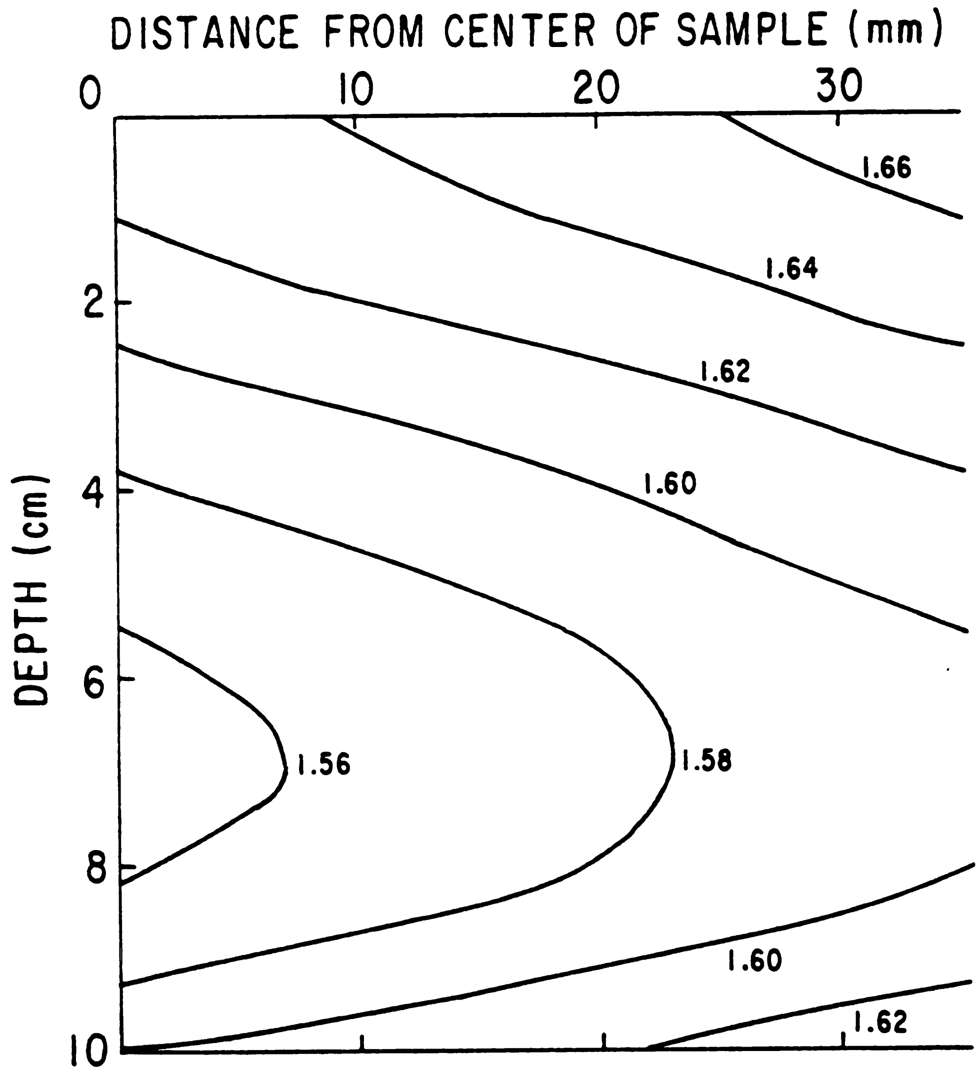

Fig. III.2. Lines of equal bulk density (g/cm^3) observed in the uncored soil.

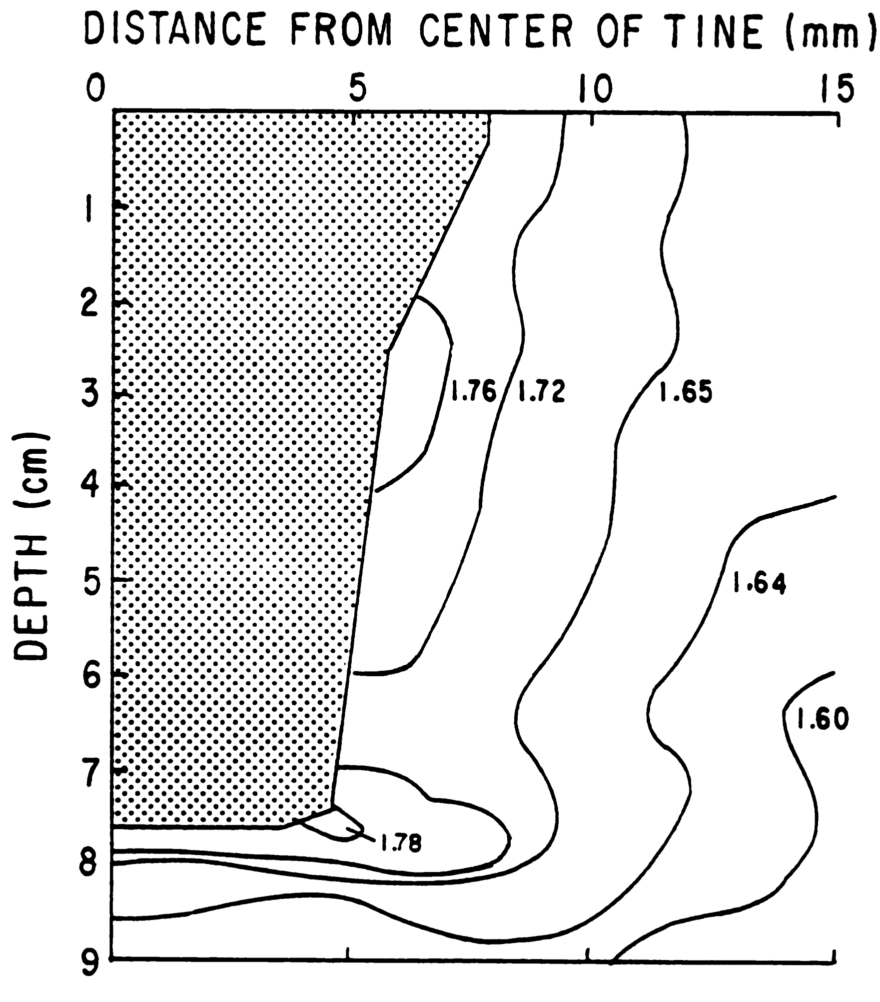

Fig. III.3. Lines of equal bulk density (g/cm^3) created by a 6.4 mm VOHT at a soil moisture content of 15.6%, by weight.

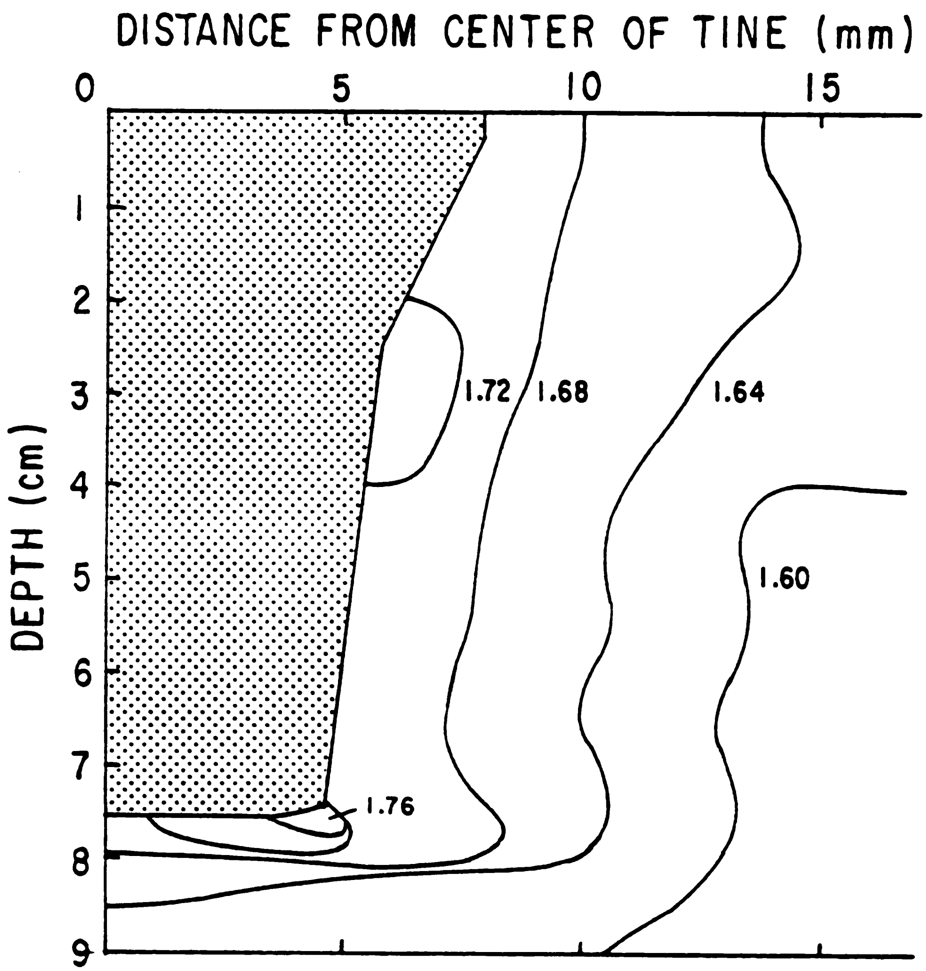

Fig. III.4. Lines of equal bulk density (g/cm^3) created by a 6.4 mm VOHT at a soil moisture content of 12.9%, by weight.

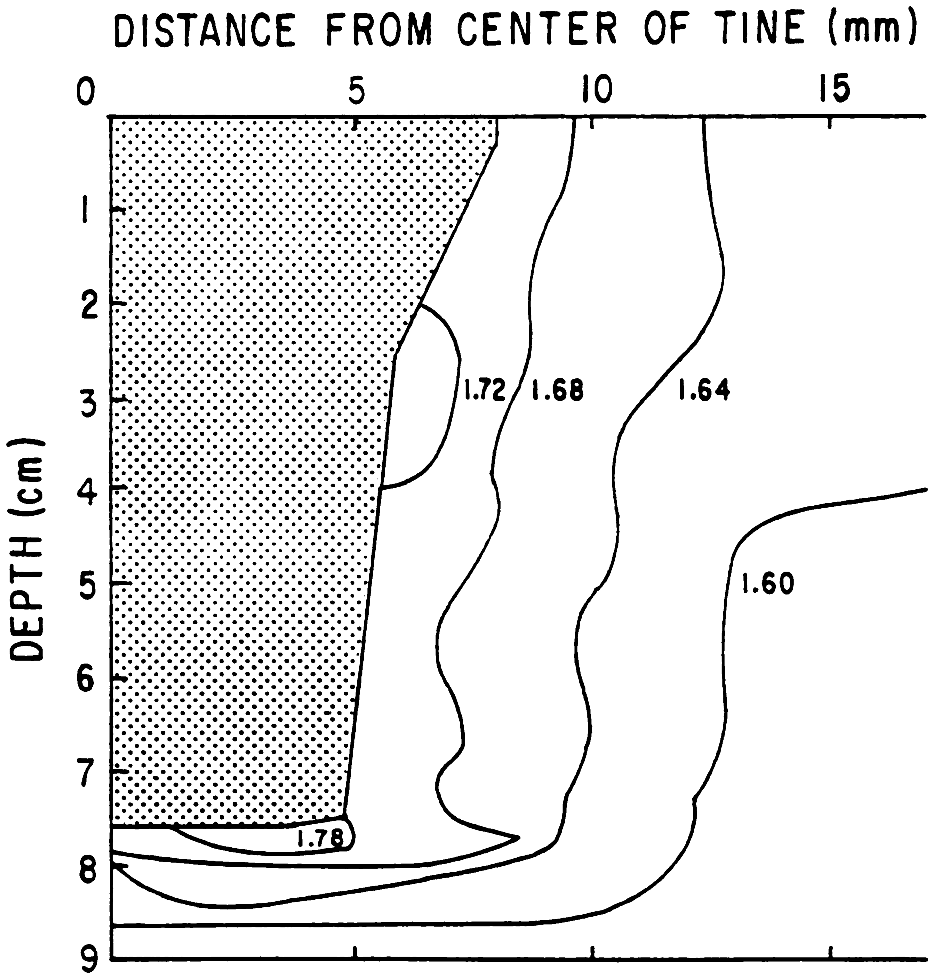

Fig. III.5. Lines of equal bulk density (g/cm^3) created by a 6.4 mm VOHT at a soil moisture content of 10.9%, by weight.

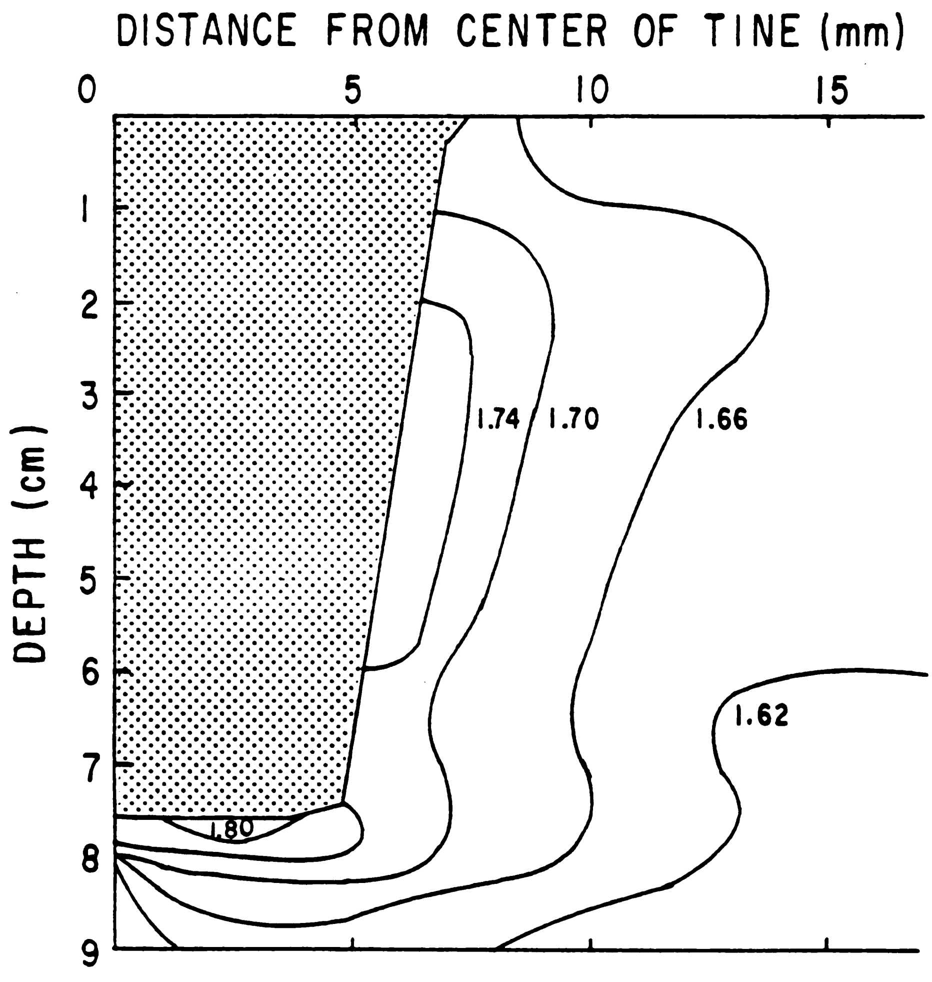

Fig. III.6. Lines of equal bulk density (g/cm^3) created by a 9.5 mm VOHT at a soil moisture content of 15.6%, by weight.

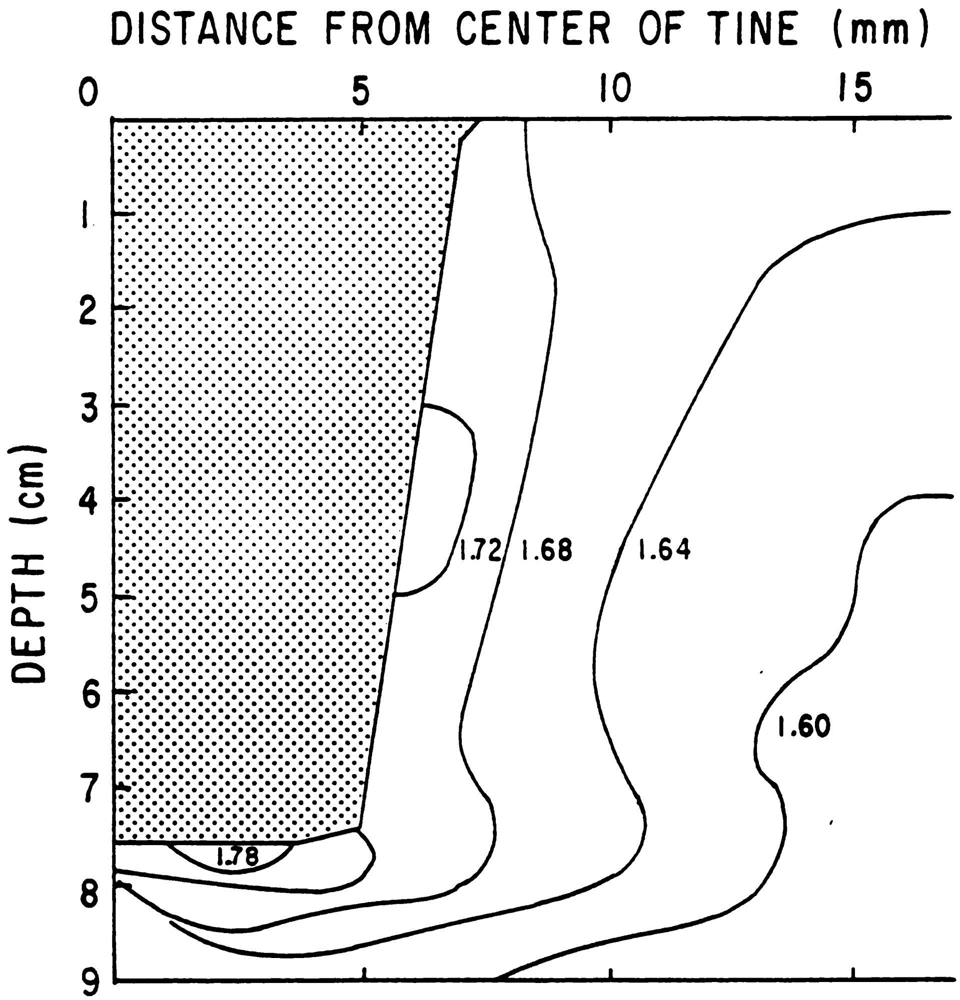

Fig. III.7. Lines of equal bulk density (g/cm^3) created by a 9.5 mm VOHT at a soil moisture content of 12.9%, by weight.

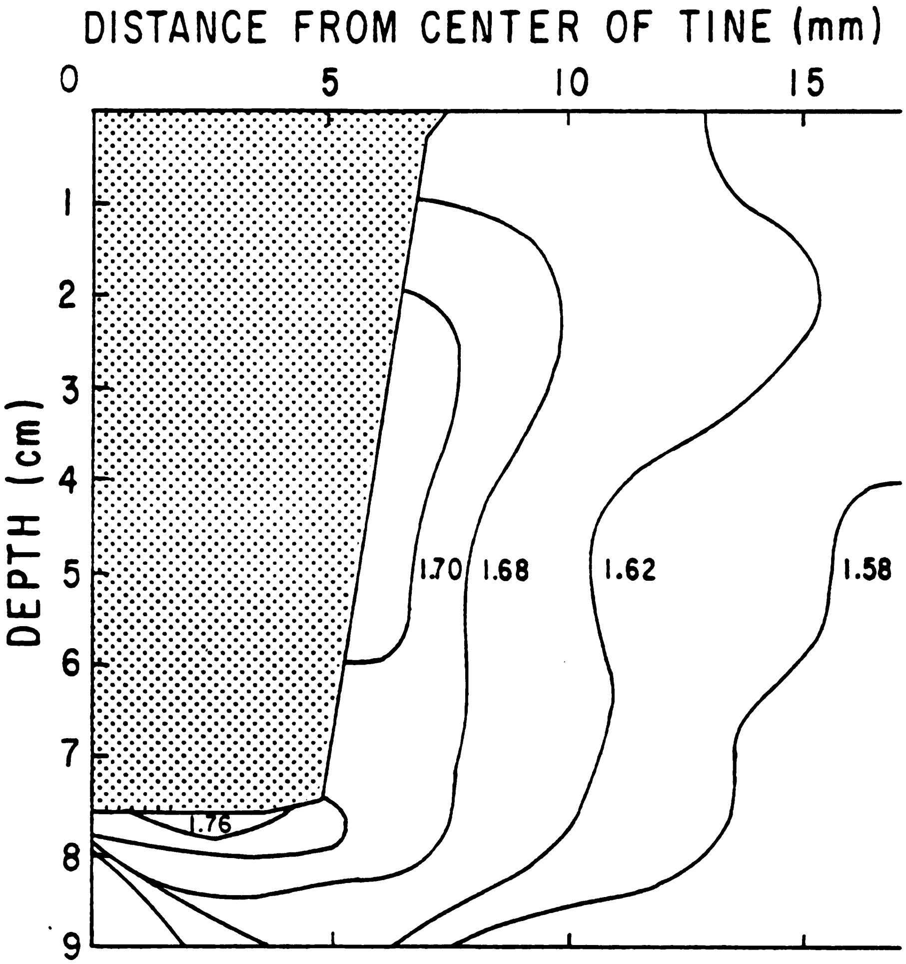

Fig. III.8. Lines of equal bulk density (g/cm^3) created by a 9.5 mm VOHT at a soil moisture content of 10.9%, by weight.

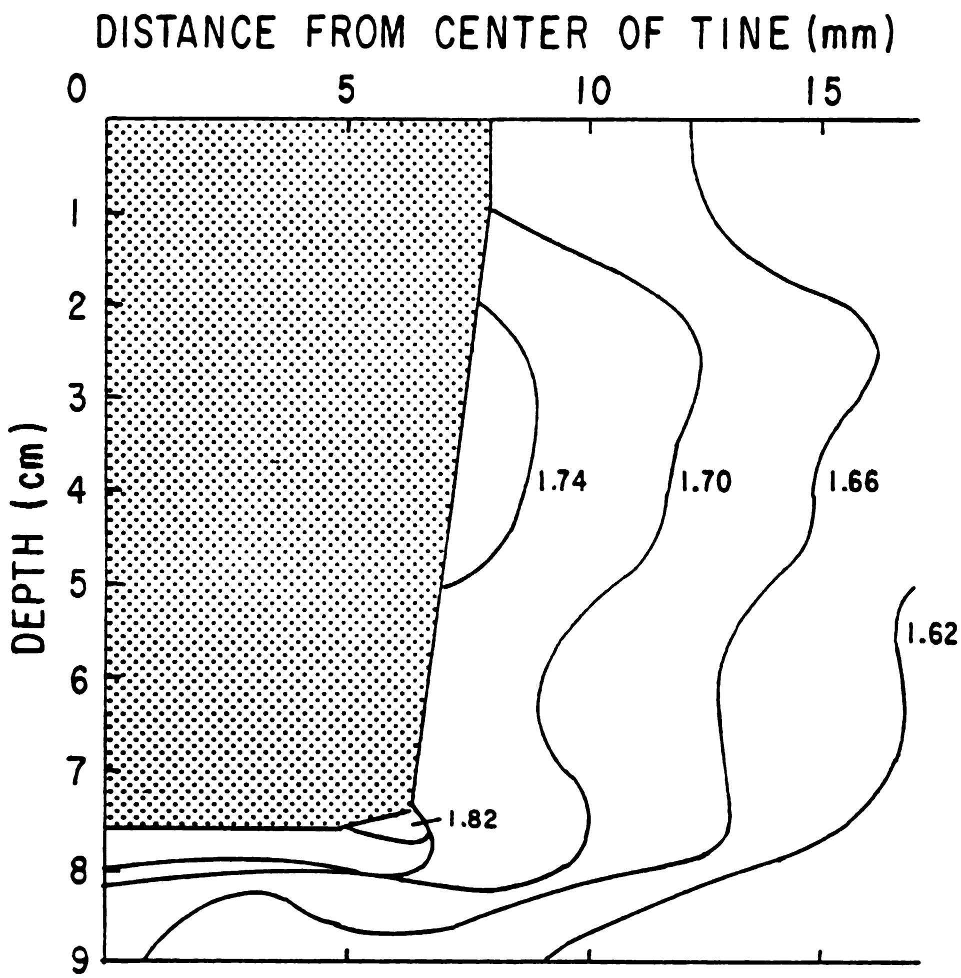

Fig. III.9. Lines of equal bulk density (g/cm^3) created by a 12.7 mm VOHT at a soil moisture content of 15.6%, by weight.

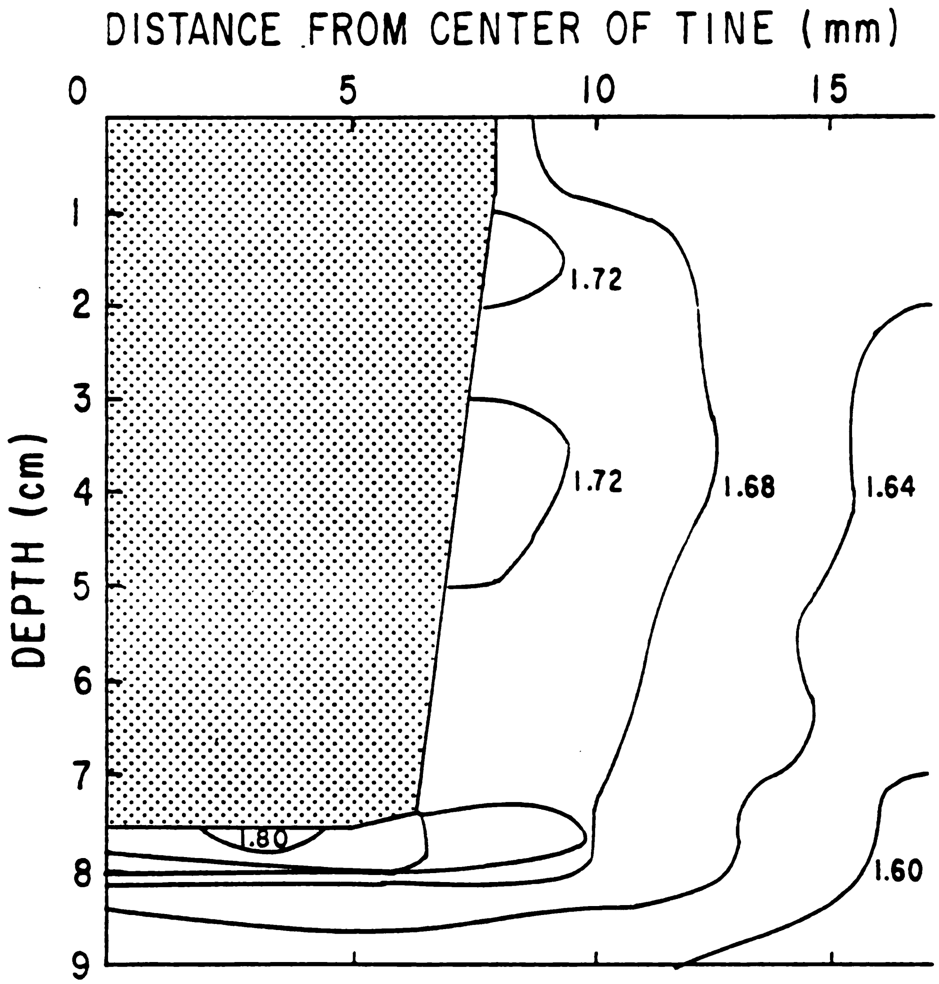

Fig. III.10. Lines of equal bulk density (g/cm^3) created by a 12.7 mm VOHT at a soil moisture content of 12.9%, by weight.

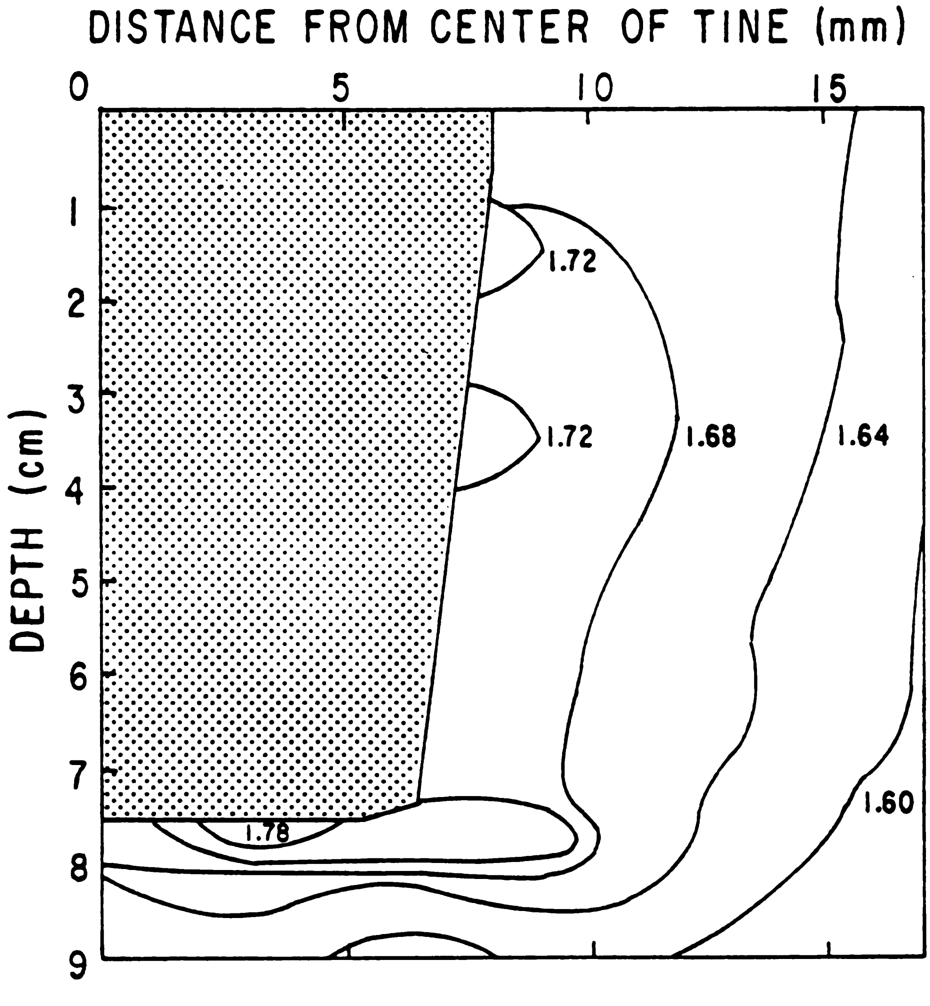

Fig. III.11. Lines of equal bulk density (g/cm^3) created by a 12.7 mm VOHT at a soil moisture content of 10.9%, by weight.

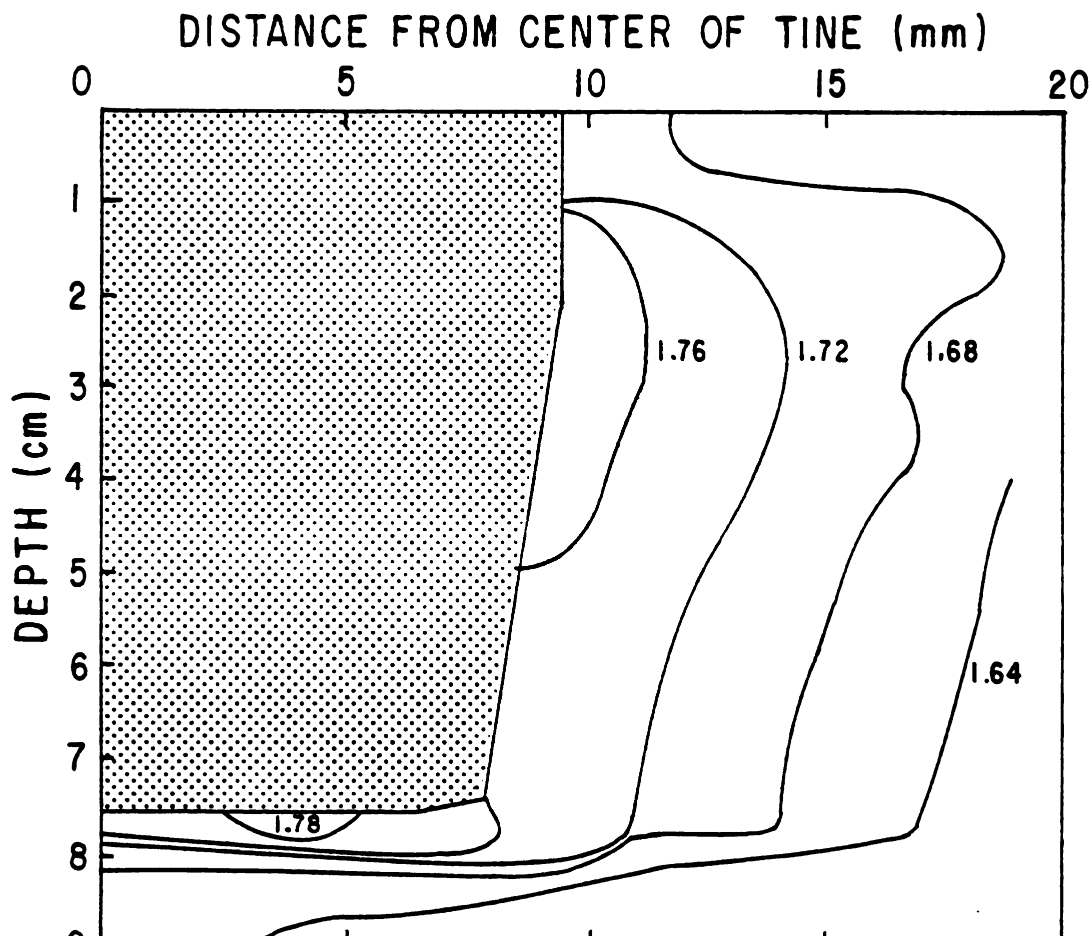

Fig. III.12. Lines of equal bulk density (g/cm^3) created by a 15.9 mm VOHT at a soil moisture content of 15.6%, by weight.

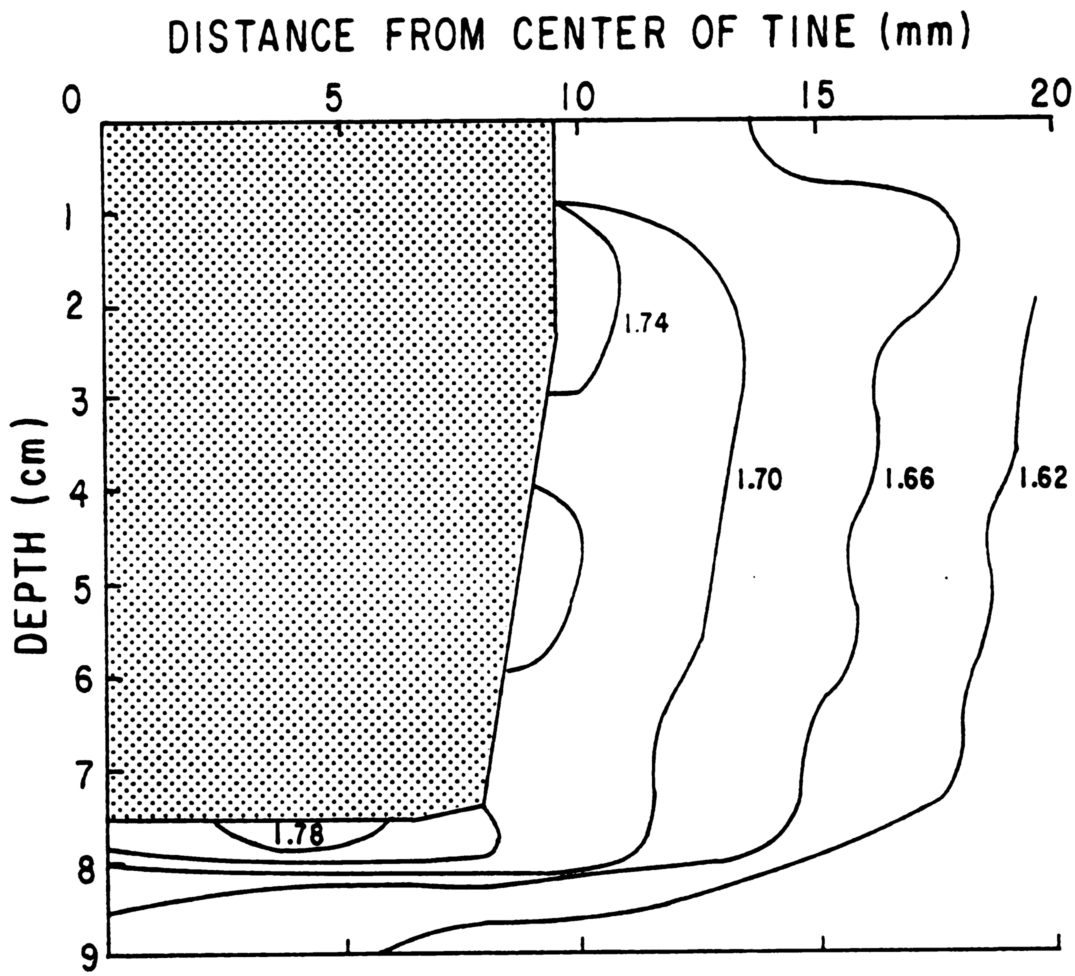

Fig. III.13. Lines of equal bulk density (g/cm^3) created by a 15.9 mm VOHT at a soil moisture content of 12.9%, by weight.

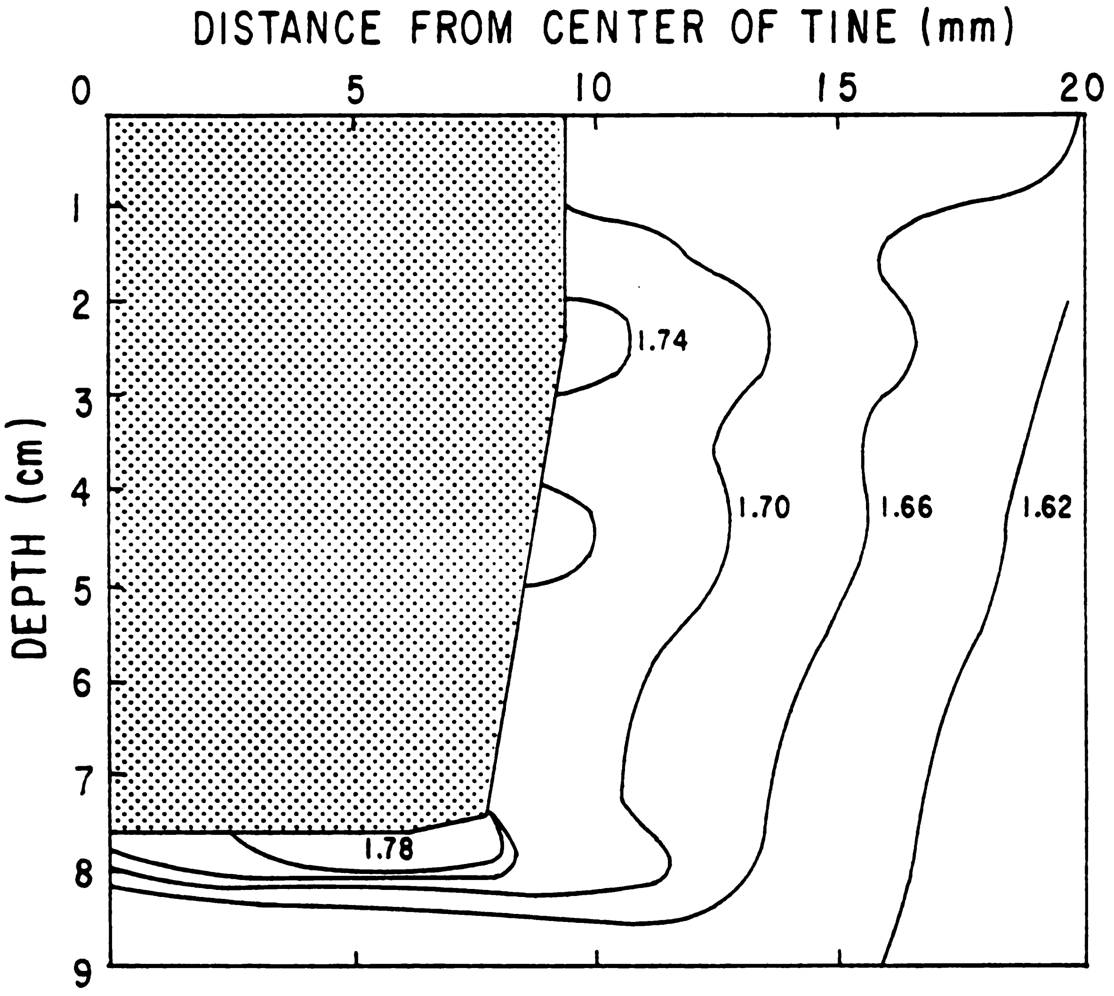

Fig. III.14. Lines of equal bulk density (g/cm^3) created by a 15.9 mm VOHT at a soil moisture content of 10.9%, by weight.

Table III.1. Physical properties of Metea fine sandy loam soil.

Sand analysis									Moisture content range, by weight		
Size range, mm						Mechanical Analysis			Soil matric potential, -cbar		
>2	2-1	1-.5	.5-.25	.25-.1	.1-.05	Sand	Silt	Clay	9.5	15	35
2.4	0.8	3.0	21.5	35.3	10.0	73	18.6	8.4	17-15†	13.5-12.5	11.5-10

†Lower plastic limit is 16.1%

Table III.2. Coefficients and coefficients of determination (R^2) for multiple regression equations developed from density in the side wall region.

Distance from soil surface	Coefficients a	b	c	d	e	f	g	h	R^2
-mm-									
				6.4 mm Tine					
0-8	-	-	-	-	0.0141	0.0033	-0.0394**	1.489	0.664**
10-18	-	-	-	-	0.0121*	0.0036	-0.0355**	1.524	0.733**
20-28	-	-	-	-	0.023**	0.0126**	-0.050**	1.351	0.880**
30-38	-	-	-	-	0.0219**	0.0151*	-0.0517**	1.364	0.855**
40-48	0.0237**	0.0222**	-0.0146**	1.319	-	-	-	-	0.865**
50-58	0.018**	0.0187	-0.0137**	1.418	-	-	-	-	0.841**
60-68	0.0067	-0.002	-0.0145**	1.631	-	-	-	-	0.799**
70-73	0.0094**	0.0033	-0.0148**	1.599	-	-	-	-	0.758**
				9.5 mm Tine					
0-8	-	-	-	-	-0.0196*	-0.011*	-0.0154*	2.075	0.292
10-18	-	-	-	-	0.0082	0.0005	-0.0341**	1.594	0.649**
20-28	-	-	-	-	0.014**	0.0051	-0.0426**	1.493	0.778**
30-38	-	-	-	-	0.0115**	0.004	-0.051**	1.548	0.864**
40-48	-	-	-	-	0.011**	0.0018	-0.054**	1.569	0.864**
50-58	-	-	-	-	0.0122**	0.0059	-0.0514**	1.532	0.836**
60-68	0.0089**	0.0081	-0.0132**	1.563	-	-	-	-	0.838**
70-73	0.0037	-0.010	-0.0134**	1.683	-	-	-	-	0.873**
				12.7 mm Tine					
0-8	-	-	-	-	0.0013	-0.0004	-0.0154*	1.668	0.157
10-18	-	-	-	-	-0.0092	-0.0049*	-0.0389**	1.918	0.714**
20-28	0.0104*	0.0023	-0.0105**	1.570	-	-	-	-	0.824**
30-38	0.0047	0.0003	-0.0132**	1.685	-	-	-	-	0.909**
40-48	0.0049	-0.0008	-0.0124**	1.682	-	-	-	-	0.865**
50-58	-0.0022	-0.0073	-0.0110**	1.794	-	-	-	-	0.804**
60-68	-0.0066	-0.020	-0.0106**	1.881	-	-	-	-	0.777**
70-73	0.0156	0.0320	-0.0135**	1.458	-	-	-	-	0.815**
				15.9 mm Tine					
0-8	0.0144	0.0018	0.0015	1.426	-	-	-	-	0.090
10-18	-	-	-	-	0.0121	0.0016	-0.0391**	1.558	0.811**
20-28	0.0229*	0.00714**	-0.0137**	1.351	-	-	-	-	0.890**
30-38	0.0172**	0.0048	-0.0127**	1.472	-	-	-	-	0.890**
40-48	0.0151*	0.0073	-0.0142**	1.494	-	-	-	-	0.880**
50-58	0.0046	-0.0007	-0.0129**	1.698	-	-	-	-	0.867**
60-68	0.0070	0.0015	-0.0126**	1.645	-	-	-	-	0.795**
70-73	0.0042	-0.0043	-0.0130**	1.704	-	-	-	-	0.778**

**, *Significant at the 1% and 5% levels, respectively.

†Coefficients in the following equations: $Y = aX_1 + bX_2 + cX_3 + d$; $Y = eX_1 + fX_2 + g \ln X_3 + h$ where Y is bulk density, X_1 is per cent soil moisture content, X_2 is force of tine penetration and X_3 is horizontal distance away from the edge of the coring hole.

Table III.3. Coefficients and the coefficients of determination (R^2) for multiple regression equations developed from vertical sections below the bottom of the coring hole.

Horizontal distance from edge of coring hole	Coefficients									
	a	b	c	d	e	f	g	h	i	R^2
-mm-					6.4 mm Tine					
-4.8	-5.0×10^{-4}	-0.048**	0.2281**	-0.10811**	0.020172**	-1.6495×10^{-3}**	4.92×10^{-5}**	-	1.578	0.99[illegible]**
-2.4	-1.0×10^{-4}	-5.5×10^{-3}	0.1784**	-0.0921**	0.017626**	-1.4661×10^{-3}**	4.438×10^{-5}**	-	1.638	0.747**
0	9.6×10^{-3}**	0.042	0.0228	-0.01674**	2.089×10^{-3}**	-7.903×10^{-5}*	-	-	1.619	0.865**
3.6	0.0208**	0.12**	-0.0435**	-	-	-	-	-	1.409	0.741**
6.6	2.1×10^{-3}	0.031	-9.1×10^{-3}	-	-	-	-	-	1.586	0.127
					9.5 mm Tine					
-4.9	-4.6×10^{-3}	-0.131*	0.3204**	-0.18729**	0.046756**	-6.11995×10^{-3}**	3.9685×10^{-5}*	-1.0079×10^{-5}*	1.712	0.774**
-2.5	1.5×10^{-3}	-0.057	0.2304**	-0.10318**	0.018115**	-1.40637×10^{-3}**	4.003×10^{-5}**	-	1.627	0.766**
0	7.7×10^{-3}	-0.017	0.0398**	-0.01546**	1.715×10^{-3}**	-6.3×10^{-5}*	-	-	1.620	0.781**
3.8	3.0×10^{-3}	-0.055	0.0116	-0.00611	8.08×10^{-4}	-3.492×10^{-5}	-	-	1.652	0.629**
7.3	2.75×10^{-3}	5.9×10^{-3}	2.0×10^{-4}	-	-	-	-	-	1.570	0.076
					12.7 mm Tine					
-6.4	0.0149	0.13	0.1555**	-0.04998**	5.4717×10^{-3}**	-1.9786×10^{-4}**	-	-	1.320	0.664**
-3.2	1.6×10^{-3}	0.034	0.2344**	-0.10184**	0.0169659**	-1.25417×10^{-3}**	3.4412×10^{-5}**	-	1.576	0.812**
0	8.0×10^{-3}	0.036	0.0667**	-0.02967**	3.5453×10^{-3}**	-1.34835×10^{-4}**	-	-	1.623	0.838**
3.3	9×10^{-4}	-0.047	0.0173	-0.01125*	1.4299×10^{-3}*	-5.681×10^{-5}	-	-	1.745	0.759**
6.7	-3.8×10^{-3}	-0.024	-4.3×10^{-3}*	-	-	-	-	-	1.717	0.329
					15.9 mm Tine					
-8	6.3×10^{-3}	0.062*	0.2243**	-0.09961**	0.0177142**	-1.40268×10^{-3}**	4.096×10^{-5}**	-	1.457	0.773**
-4	-3.5×10^{-3}	-0.025	0.1487**	-0.04902**	5.355×10^{-3}**	-1.9228×10^{-4}**	-	-	1.708	0.785**
0	-8.1×10^{-3}*	-0.131**	0.0614**	-0.02139**	2.1639×10^{-3}**	-7.239×10^{-5}*	-	-	1.919	0.804**
3.3	-0.015**	-0.158**	-9.5×10^{-3}**	-	-	-	-	-	2.025	0.674**
8.2	-7.5×10^{-3}	-0.081*	-2.0×10^{-3}*	-	-	-	-	-	1.781	0.146

**, *Significant at the 1% and 5% level, respectively.
-Coefficients in the following equation: $Y = aX_1 + bX_2 + cX_3 + dX_3^2 + eX_3^3 + fX_3^4 + gX_3^5 + hX_3^6 + i$ where Y is bulk density, X_1 is per cent soil moisture X_2 is average force of tine penetration caused by the lower lip of the tine, and X_3 is the vertical distance below the bottom of the coring hole.

Table III.4. Parameters used in Equations [2] through [5] to develop density isograms.

Soil depth	Soil moisture (X_1)	Tine penetration force, X_2 — Tine size, mm: 6.4	9.5	12.7	15.9
-mm-	-%-	kg			
0-8	15.6	8.1†	9.7	11.8	16.4
0-8	12.9	12.1	12.8	15.7	22.9
0-8	10.9	17.5	20.4	25.6	32.8
10-18	15.6	6.0	7.9	9.6	13.3
10-18	12.9	9.1	10.2	13.1	19.1
10-18	10.9	13.3	16.1	20.5	27.3
20-28	15.6	4.7	6.3	7.7	10.7
20-28	12.9	7.1	8.4	10.3	15.3
20-28	10.9	10.3	13.2	16.3	22.0
30-38	15.6	3.7	5.1	6.1	8.6
30-38	12.9	5.6	6.6	8.2	11.9
30-38	10.9	7.9	10.7	12.8	17.2
40-48	15.6	2.9	4.1	4.8	6.7
40-48	12.9	4.1	5.2	6.4	9.2
40-48	10.9	6.2	8.5	9.9	13.2
50-58	15.6	2.3	3.2	3.6	5.2
50-58	12.9	3.4	4.1	5.0	6.9
50-58	10.9	4.7	6.6	7.7	10.0
60-68	15.6	1.7	2.3	2.6	3.8
60-68	12.9	2.4	3.2	3.6	4.9
60-68	10.9	3.4	4.6	4.9	7.0
70-73	15.6	0.9	1.3	1.5	2.2
70-73	12.9	1.6	2.1	2.2	2.9
70-73	10.9	2.3	2.9	2.9	3.9
76-88	15.6	0.16	0.38	0.69	0.55
76-88	12.9	0.33	0.47	0.70	0.78
76-88	10.9	0.59	0.71	0.60	0.72

†Average of 3 values obtained from study.

Table III.5. Average reduction in overall soil bulk density following VOHT core cultivation.

Tine size	Bulk density reduction Soil moisture potential, -cbar 9.5	15	35
- mm -	------------ mg/cm^3	------------	
6.4	14.3 bcde*	11.3 cde	10.0 de
9.5	13.0 bcde	9.7 de	8.3 e
12.7	17.3 bcd	20.0 bc	21.0 b
15.9	31.7 a	32.0 a	31.3 a

*Values with columns or rows followed by the same letter are not significantly different at the 5% level.

CHAPTER IV

SOIL COMPACTION INDUCING EFFECTS OF VERTICAL OPERATING HOLLOW TINE (VOHT) TURFGRASS CULTIVATION, GREENHOUSE AND FIELD RESULTS

ABSTRACT

VOHT (vertical operating hollow tine) turfgrass cultivation is a common cultural practice used on putting greens. Little research has been published on the effects of VOHT coring on soil structure.

In a 2-year field study conducted on a Metea sandy loam soil that was maintained under putting green conditions, VOHT coring was found to have no consistent effect on oxygen diffusion rates, turfgrass quality and soil strength.

Results from a greenhouse study conducted under similar conditions as the field experiment, revealed that VOHT coring caused a large increase in soil bulk density surrounding the coring hole for 9.5 and 15.9 mm diameter tines. The degree of increased density from coring was greater on a soil with a lower initial bulk density than on a more highly compacted soil. The sides of the coring holes had not collapsed after 14 days but did collapse 93 days after coring. The degree of compaction observed below the coring hole was similar at 14 and 93 days following coring, indicating that repeated VOHT coring could induce the development of a compacted soil layer below the depth of coring.

The benificel effects from the reduction in surface compaction caused by VOHT coring should, however, outweigh the potential problems associated

with the long term development of a compacted layer below the depth of coring.

INTRODUCTION

Vertical operating hollow tine (VOHT) turfgrass cultivation is a common management practice used on putting greens. The objectives of VOHT coring are to alleviate surface soil compaction problems, remove unwanted soil layers near the surface and to help reduce thatch accumulation. However, limited research has been published in support of these objectives.

Murray and Juska (10) found that coring reduced thatch levels, whereas Engel and Alderfer (7) observed that thatch accumulation was not significantly reduced by coring. Water infiltration rates have been found to be unaffected (4), reduced (15) or increased (16) following VOHT cultivation.

As noted in an earlier section, Petrovic et al. (13) found that VOHT coring caused a large increase in bulk density in the soil surrounding the coring hole in a moderately compacted soil under laboratory conditions. That research did not determine what the effects of the growing turf plants, other natural processes such as soil wetting and drying cycles, and a soil at a higher degree of compaction would have on the results they observed.

The degree to which a soil will compress is related to both the soil moisture content and the extent to which the soil is already compressed. This theory developed by Doner (6) and confirmed by Reaves and Nichols (14) states that an increment increase in compression of a non-plastic granular medium at a specific compacting pressure is proportional to the soil moisture content and to the degree the soil is already compressed. The amount of compression (compaction) increases with increasing soil moisture content from air dry to the lower plastic limit (LPL). The amount of compression is reduced, however, when soil moisture content increases past the LPL. The LPL is defined as the minimum moisture content at which the soil particles are sufficiently lubricated so that an applied pressure will cause a perminant change in their size and shape (2).

The objectives of the research reported here were to examine the effects of VOHT coring, under both greenhouse and field conditions on soil structure and turfgrass quality as influenced by 1) the degree of soil compaction and 2) the soil moisture content at the time of coring.

MATERIALS AND METHODS

Field Study

A VOHT field cultivation study was conducted at the Michigan State University Soil Science Research Farm at East Lansing on a Metea fine sandy loam soil (loamy, mixed, mesic Arenic Hapludalf). The soil was found to have 73% sand, 18.6% silt, 8.4% clay, 1.1% organic matter, a pH of 6.9 and LPL at 16.1% by weight. The sand content was further characterized by wet sieving analysis with the following results: 2.4% > 2 mm; 0.8% from 2-1 mm; 3.0% from 1-0.5 mm; 21.5% from 0.5-0.25 mm; 35.3% from 0.25-0.1 mm and 10% from 0.1-0.053 mm.

In June 1976, the experimental site was seeded to Penncross creeping bentgrass (Agrostis palustris Huds.). A cutting height of 6.4 mm was maintained throughout the study. Total N, P_2O_5, and K_2O applied in 1976 were 171, 49 and 49 kg/ha, respectively.

VOHT coring treatments were initiated in 1977 on 2.7 x 4.6 m main plots arranged in a randomized complete block design. Each main plot was split with half of each plot receiving frequent compaction applications. Three replications of each treatment were included.

Coring treatments with a Ryan's[R] Greensaire aerfier, model A-5, consisted of using 9.5 and 12.7 mm diameter tines to core plots at soil moisture potentials of 0, -10 and -33 cbar. An uncored plot was included for comparison. Coring treatments were applied on July 26 through July 29 and on October 7 through 13 in 1977 and in 1978 on May 31 through June 6 and on October 12 through 18.

At the time of coring, soil moisture potentials were monitored by tensiometers placed 7.6 to 10.2 cm below the turf surface and were maintained within the following limits: 0-1, -10 $\pm$ 1.5 and -33 $\pm$ 8 cbar. Soil samples taken at the depth of the tensiometer placement during the coring operation revealed that the 0, -10 and -33 cbar moisture potentials corresponded to moisture contents by weight of 23 to 19.5%, 18-15% and 12 to 9%, respectively.

Compaction treatments that averaged twice weekly were initiated on July 28 and May 5 and were terminated on October 31 and October 26 in 1977 and 1978, respectively. One pass with a Ryan's[R] water-filled vibrating power roller, that had 12 golf soils with spikes adhered to the roller surface, comprised the compaction treatments.

The total amount of N, P_2O_5, K_2O applied in 1977 and 1978 were 147, 31, 37 and 171, 37, 48 kg/ha, respectively. Fungicides were applied as needed to control diseases. Supplemental irrigation was used as needed to prevent wilt. Penetrometer readings, oxygen diffusion rates (ODRs) and bulk density analyses were used to characterize soil structural changes resulting from VOHT coring.

A depth monitoring penetrometer (5) was used to take 10 readings per plot at locations equidistant from the center of the coring holes. The measurements were made on October 28, 1978. Soil moisture content at the time of the penetrometer measurements was 20.7% ± 1.2, by weight.

ODR's were determined by the platinum microelectrode technique (8) on August 9 and 21, 1978 when the soil moisture potential was within 1 cbar of saturation. Twenty readings per plot were made with electrodes placed 5 cm deep equidistant from the center of surrounding coring holes.

Two soil core samples, 7.36 cm I.D. x 12.5 cm deep were taken from each plot on November 24-25, 1978 for computed tomographic (12) bulk density analyses.

Greenhouse Study

The experiment was conducted during the period of January 26 through May 24, 1979. Surface soil was collected adjacent to the field plots having the physical and chemical properties as described previously. The soil was air dried and passed through a 1.00 mm sieve.

The experimental design used was a $5x2^2$ factorial with 3 replicates arranged in randomized complete blocks. The first factor included tine sizes of 9.5 and 15.9 mm in diameter that were used to core samples at -9.5 and -33 cbar soil moisture potentials. An uncored sample, equilibriated at -33 cbar potential, was included for comparison.

The second factor involved 2 levels of bulk density. Half of the samples were packed into 7.7 cm I.D. x 15.2 cm deep plastic tubing to a bulk density of 1.55 g/cm^3. The second group had an additional 2 cm section of plastic tubing attached to the upper surface. Thirty days after sodding, compaction was applied to the sodded surface over a 3 day period to decrease the column height by 2.0 cm (added section was removed). The bulk density of these samples was increased to 1.70 g/cm^3.

Sampling dates of 14 and 45 days following cultivation comprised the third factor.

Each pot received a plug of soil-less sod on January 20 that had been taken earlier from the field study plots. Electric trimming shears were used to mow each plot 3 times weekly at a height of 8 mm $\pm$ 2. Clippings were removed. Based on soil tests, no phosphorus was required and prior to sodding, 96 kg/ha of potassium sulfate was added to the pots and thoroughly mixed throughout the soil.

Ammonium nitrate was applied at the rate of 24.4 kg/ha on Feburary 9 and 24, March 20 and April 24. Chlorothalnil was applied to control diseases at weekly intervals at the rate of 7.84 l/ha using a small hand atomizer.

Watering was done on a set daily bases by an overhead misting system. A soil moisture content of 12 to 17% by weight was maintained in this way throughout the study. Minimum temperature was set at 18 C and a 14 hour daylight period was utilized by the addition of supplimental flourescent lighting.

VOHT coring was done by the Instron method (11) to a depth of 76 mm at a vertical tine movement rate of 254 mm/min. Half the samples were cored on March 16, the other half on May 10.

To achieve soil moisture potentials of -9.5 and -33 cbar, the samples were placed on 1 bar ceramic plates, saturated in tap water for 24 hours and placed in pressure plate extractors for a 1 day period. At this time the soil moisture contents were 17 to 15% (LPL) and 12 to 10% at the -9.5 and -33 cbar potentials, respectively.

A count of the number of shoots per pot was taken on March 21 through 23 on the samples that were to be treated on May 10. These samples reflect a difference in soil bulk density that was very evident at this point.

The experiment was terminated on May 24 at which time all samples were oven dried at 55 C for at least 3 days.

A vertical cross-section of soil bulk density values were taken directly at the center of the coring hole (or center of uncored sample) by the computed tomographic technique (12). Earlier research conducted under laboratory conditions (13) revealed that the zones of greatest induced compaction caused by a 9.5 and 15.9 mm tines were 2 and 4 cm below the soil surface at the sides of the coring hole, respectively. Also, it was found that the 9.5 and 15.9 cm tines caused the greatest compaction midway between the edge and center of the tine and directly below the edge of the coring hole, respectively.

These same locations were selected for bulk density analysis in this study. For the region of soil at the sides of the coring hole, a horizontal section 8 mm high x 30 mm wide, at 2 and 4 cm below the soil surface for the 9.5 and 15.9 cm tines, respectively, was used for bulk density comparisons. Below the coring hole, bulk density was obtained in 2 mm wide by 12 mm long vertical section at location described above.

RESULTS AND DISCUSSION

VOHT Greenhouse Study

A highly significant reduction in shoot density occurred with an increase in bulk density. Shoot densities were 14.9 and 11.6 shoots/cm^2 at bulk densities of 1.55 and 170 g/cm^3, respectively.

The effects of VOHT coring on the soil bulk density at selected regions in the cultivation zone are shown in Tables IV.1 and IV.2. The data are for only 2 replicates and represent the change in density that occurred when compared to the same locations in the uncored soil.

In general, the edges of most of the coring holes were intact 14 days (May 10) following cultivation but had totally collapsed after 93 days. (March 16) The maximum density occurred within 2 mm of the hole and density decreased rapidly with distance away from the hole. This was consistent with what was found in an earlier study (13).

Increases in bulk density of less than 100, 100 to 200 and > 200 mg/cm^3 wwere assumed to be slight, moderate and severe increase in compaction, respectively.

The initial soil bulk density had a marked effect on the degree to which VOHT coring caused an increase in bulk density in the soil surrounding the coring hole. At the lower bulk density of 1.55 g/cm^3, both tine sizes caused severe to moderate increases in compaction in the soil below the coring hole, whereas, at the higher bulk density of 1.70 g/cm^3, compaction was only moderate to slight. This would be predicted from the findings of Doner (6) and Reaves and Nichols (14).

The soil moisture content influenced the degree of compaction induced by the 15.9 mm tine. At the lower bulk density the 15.9 mm tine caused a severe increase in compaction below the coring at the -9.5 cbar potential; however, when the soil was drier (-33 cbar) there was only a moderate level of compaction. Others (6,14) have observed the degree of compaction is less when the soil is drier.

The amount of compaction induced at the sides of the coring hole by VOHT cultivation was more evident at 14 days (May 10) following coring than after 93 days (March 16). In contrast, the soil below the coring hole was observed to be at the same relative degree of compaction at both 14 and 93 days following coring.

VOHT Field Study

The effects of VOHT coring on oxygen diffusion rates (ODR's) are shown in Table IV.3. All ODR's were well above the 15 g O_2 x $10^{-8}cm^{-2}$ min^{1} standard at which root growth of certain turfgrass species has been found to be limited by ODR (9). It is apparent that even at or near saturated soil moisture conditions, cultivation and supplemental compaction had no consistent effects on ODR. Lack of improvement in ODR resulting from VOHT cultivation rated here might be attributed to the short duration of this study. Engel and Alderfer (7) noted that VOHT cultivation caused a 20% increase in ODR in the tenth year of a field study.

Compaction has been shown to reduce ODR (9). This would indicate that the level of compaction of this soil was not great enough to cause a reduction in ODR.

Penetrometer readings (see Table IV.4), used to measure soil strength, showed a marked increase from the compaction treatments consistent with what others have found (1,3). The VOHT coring did not significantly influence soil strength at the 5% level. However, at the 10% level, VOHT coring with a 12.7 mm tine at a soil moisture potential of -10 cbar caused an increase in soil strength in the 6 to 10 cm depth below the turf surface. This increase in soil strength would indicate that a compacted layer of soil was developing below the depth of cultivation by repeated VOHT coring. This compacted layer would confirm the results observed in the greenhouse study and in a previous laboratory experiment (13).

Since the overall turfgrass quality was not significantly influenced by VOHT coring the data are not reported. Compaction did cause a slight reduction in quality midway through the second summer. Murray and Juska (10) observed that coring caused an increase in Kentucky bluegrass (Poa *pratensis*. L) quality, whereas Engel and Alderfer (7) found no effect on Penncross creeping bentgrass. It is evident that a positive quality response from core cultivation is dependent on both the species of turfgrass used and the conditions of the turf and soil.

SUMMARY

It is evident that a moderately compacted soil, in this case at a bulk density of 1.55 g/cm^3, would show a greater degree of compaction induced by VOHT coring than in a more highly compacted soil. The compaction created at the sides of the coring hole would appear to have little long term negative effect on overall turfgrass quality. However, the zone of compaction created in the soil below the coring hole by VOHT cultivation was still present after 93 days. This could pose a long term problem since VOHT coring is often done 2 times a year, occasionally more often, and could lead to the development of a compacted layer of soil below the depth of coring. This could result in the impedence of water movement, gas exchange and root growth below this zone. Still the benifits of VOHT coring may very well out-weigh the potential problems associated with a compacted layer of soil below the cultivation depth.

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Table IV.1. Average increase in soil bulk density following VOHT core cultivation with a 9.5 mm tine. Date shown is the average of 2 replications.

Initial bulk density	Soil moisture potential	Days following coring	Depth below soil surface	Distance from edge of coring hole, mm							
				0	2	4	6	8	10	12	15
g/cm^3	-cbar		cm	mg/cm^3							
1.55	9.5	93	2†	14	57	90	87	69	56	55	53
1.55	9.5	93	7.6-8.8	148	270	257	168	123	98	73	-
1.55	9.5	14	2	97	201	179	168	155	135	112	76
1.55	9.5	14	7.6-8.8	154	245	245	169	148	79	62	-
1.70	9.5	93	2	79	112	68	73	56	47	47	47
1.70	9.5	93	7.6-8.8	99	213	158	24	100	51	30	-
1.70	9.5	14	2	-123	129	110	91	40	36	39	42
1.70	9.5	14	7.6-8.8	-1	158	102	35	-4	-4	-40	-
1.55	33	93	2	65	88	128	119	114	74	67	51
1.55	33	93	7.6-8.8	165	276	258	174	134	75	61	-
1.55	33	14	2	67	117	93	97	117	106	93	82
1.55	33	14	7.6-8.8	226	345	250	166	63	84	80	-
1.70	33	93	2	79	127	119	139	122	77	97	117
1.70	33	93	7.6-8.8	55	139	108	55	62	33	36	-
1.70	33	14	2	-20	21	43	58	33	45	46	40
1.70	33	14	7.6-8.8	63	70	76	32	-10	-20	-58	-

Table IV.2. Average increase in soil bulk density following VOHT core cultivation with a 15.9 mm tine. Data shown is the average of 2 replications.

Initial bulk Density	Days moisture potential	Days following coring	Depth below soil surface	Distance from edge of coring hole, mm							
				0	2	4	6	8	10	12	15
g/cm^3	-cbar		cm	mg/cm^3							
1.55	9.5	93	4	119	123	114	64	80	75	79	82
1.55	9.5	93	7.6-8.8	214	277	227	165	138	128	121	-
1.55	9.5	14	4	-12	263	252	197	147	119	94	66
1.55	9.5	14	7.6-8.8	114	256	255	184	113	56	36	-
1.70	9.5	93	4	-75	41	77	59	40	51	42	33
1.70	9.5	93	7.6-8.8	83	94	125	30	117	61	45	-
1.70	9.5	14	4	-76	216	166	134	64	11	15	11
1.70	9.5	14	7.6-8.8	59	187	173	99	51	16	-32	-
1.55	33	93	4	94	108	128	104	86	61	53	41
1.55	33	93	7.6-8.8	140	208	208	117	58	9	68	-
1.55	33	14	4	16	86	120	94	85	71	73	80
1.55	33	14	7.6-8.8	136	228	204	111	54	58	72	-
1.70	33	93	4	-295	119	114	112	139	26	52	76
1.70	33	93	7.6-8.8	137	196	159	46	136	88	67	-
1.70	33	14	4	59	13	-16	-11	-8	-9	-7	-1
1.70	33	14	7.6-8.8	173	157	155	120	65	25	-20	-

Table IV.3 Average oxygen diffusion rates (ODR) obtained in the VOHT field study.

Tine size	Soil moisture potential	Compaction†	Measurement date 8/9/78	Measurement date 8/21/78
mm	-cbar		$gO_2 x 10^{-8}$	$cm^{-2} min^{-1}$
0	-	+	24.0‡	24.7
0	-	-	25.3	20.5
9.5	0	+	28.0	25.2
9.5	0	-	30.4	21.0
9.5	10	+	28.8	22.9
9.5	10	-	29.1	23.0
9.5	33	+	25.8	22.2
9.5	33	-	27.5	24.0
12.7	0	+	26.7	21.7
12.7	0	-	22.9	19.7
12.7	10	+	25.0	21.9
12.7	10	-	26.8	20.7
12.7	33	+	24.0	19.8
12.7	33	-	30.3	22.7

† +/- refer to with and without compaction treatments.

‡ Each value represents an average of 60 readings.

Table IV. 4. Average penetrometer reading obtained at various points below the soil surface in the VOHT field study.

Tine size	Soil moisture potential	Compaction†	Distance below soil surface, cm				
			2	6	8	10	12
mm	-cbar		bar				
0	-	+	31.2‡	33.4	33.8	33.4	32.7
0	-	-	23.6	26.7	27.8	27.5	27.0
9.5	0	+	25.6	30.9	32.1	33.2	30.5
9.5	0	-	19.9	24.1	26.4	26.5	26.6
9.5	10	+	28.5	35.8	36.8	36.3	34.2
9.5	10	-	18.8	26.1	29.2	29.9	29.5
9.5	33	+	29.7	33.2	33.3	32.1	31.0
9.5	33	-	22.5	27.0	28.6	28.9	27.9
12.7	0	+	29.3	34.7	35.5	37.7	34.0
12.7	0	-	20.6	26.0	27.8	28.2	27.0
12.7	10	+	33.0	38.6	38.9	38.5	35.3
12.7	10	-	23.1	34.0	37.2	37.9	35.1
12.7	33	+	28.9	34.0	34.9	34.6	31.2
12.7	33	-	20.3	25.4	28.1	28.6	27.7
		mean +	29.5a*	34.4 a	35.1 a	34.8 a	32.7 a
		-	21.2 b	26.9 b	29.3 b	29.6 b	28.7 b

*Values within columns followed by the same letter are not significant at the 1% level.

† +/- refers to with and without compaction treatments.

‡Each value represents an average of 30 measurements.

CONCLUSIONS

The following were the conclusions drawn from these investigations:

1. The Instron universal testing machine was found to simulate the field VOHT coring unit and can be used for laboratory and greenhouse studies;

2. Increasing the rate of tine movement with the Instron machine in laboratory studies had only a slight effect on increasing the force required for tine penetration;

3. Using the Instron machine, the increase in force associated with an increase in tine movement rate should have a negligible effect on soil bulk density;

4. The CT scanner at the Michigan State University Clinical Center responded in a linear fashion to increasing bulk density of a Metea fine sandy loam soil and glass beads-glass air-filled samples;

5. High and low contrast spatial resolution of thes CT scanner was 1.25 x 1.25 x 2.4 mm and 6.4 x 6.4 x 2.4 mm, respectively;

6. Loss of information can result from beam hardening artifacts during CT analysis, however, procedures were found to reduce the effects of such artifacts;

7. The CT scanner can be used effectively to determine soil bulk density _in situ_ with a fine 3-dimensional spatial resolution and can have wide application to the field of soil science research;

8. VOHT coring caused a large increase in bulk density in the soil surrounding the coring hole in a laboratory study;

9. Soil bulk density was at a maximum within 2 mm from the coring hole and decreased linearly away from the hole for a distance of 10 to 12 mm, beyond which no compaction was apparent;

10. Varying the tine size had only a slight effect on the maximum density observed; however, the largest tine size (15.9 mm) did cause an increase of 3.3 mm in the thickness of the soil away from the hole which had a higher bulk density after coring;

11. Soil that was drier at the time of VOHT coring had a smaller maximum density and smaller thickness of the zone of higher density at the sides of the coring hole for only the 6.4 and 9.5 mm tines;

12. Density below the coring hole was not influenced to a large extent by variations in tine size and/or soil moisture content;

13. The relative degree of increased compaction caused by VOHT coring was less at the sides of the coring hole than below the coring hole;

14. Under greenhouse conditions, VOHT coring caused a large increase in bulk density in the soil surrounding the coring hole which was still present 14 days following cultivation;

15. At 93 days following VOHT coring, the zone of increased bulk density was only present in soil below the coring hole since the side walls had collapsed;

16. VOHT coring caused a smaller increase in bulk density in the soil surrounding the coring hole in soil that had a higher initial bulk density, thus a soil with a high bulk density (highly compacted) will be less susceptible to a compacting influence with VOHT coring;

17. VOHT coring had little effect on oxygen diffusion rates, turfgrass quality and soil strength in a 2-year field study.