3-D Visualization of soil macroporosity using x-ray CAT scanning

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Perret, J., Prasher, S.O., Kantzas, A. and Langford, C. 1997. **3-D Visualization of soil macroporosity using x-ray CAT scanning.** Can. Agric. Eng. 37:249-261. Computer assisted Tomography (CAT) offers considerable potential for reliable and nondestructive in-situ characterization of macropores occurring in agricultural soils. Several researchers have used CAT techniques for characterizing soil macropores of small undisturbed soil cores. However, there is still a need to develop comprehensive algorithms to automate the analysis and interpretation of macropore geometry directly from CAT scan data. Four undisturbed soil columns (800 mm long x 77 mm diameter) were extracted from a loamy sand field in central Canada and scanned for the visualization and characterization of their interconnecting macropore structure. A total of 240 scans of 3-mm depth were taken for each column. After conversion of the raw CAT scan data into density matrices, two- and three-dimensional soil density reconstructions were generated. With the elaboration of numerous computer programs in the PV-WAVE language, this analysis gives a detailed representation of the spatial variations of the macropore structure and heterogeneity of soil.

La technique de CAT scanning (Computer Assisted Tomography) offre une opportunité unique pour la caractérisation des chemins d'écoulement préférentiel présents dans les sols agricoles. Cette approche permet de visualiser et d'étudier les macropores du sol de façon fiable et non destructive, et ainsi, de mieux comprendre le mouvement rapide de l'eau et des composés chimiques à travers le sol. Il est essentiel de quantifier ce phénomène hydrologique afin d'acquérir une meilleure compréhension de l'impact de ce phénomène sur la contamination des eaux souterraines. Le nombre de macropore par unité de surface, leur diamètre, leur orientation, leur circularité, ainsi que leur tortuosité influencent directement le phénomène de flot préférentiel et pourtant, ces paramètres ne sont pas pris en considération dans la plupart des modèles mathématiques utilisés pour la prédiction du transport de l'eau et des composés chimiques dans le sol. Dans cet article, nous présentons ces différents paramètres tel qu'évalués à l'aide de rayon X en utilisant un scanner modèle EMI CT5005. Plusieurs colonnes de sol (0.8 m x 77 mm de diamètre) ont été prélevées intactes dans un champ du centre du Canada. Un total de 240 sections de 3 mm d'épaisseur ont été scannées permettant ainsi la visualisation et l'analyse de la structure des macropores de chaque colonne. Après transformation des données brutes générées par le CAT scanner en matrices représentant la densité volumétrique du sol, la porosité de chaque colonne a été redéfinie en deux et trois dimensions. Cette analyse permet de représenter en détail la variation spatiale des chemins d'écoulement préférentiel ainsi que les hétérogénéités du sol.

INTRODUCTION

A number of investigators have established that the presence of macropores results in rapid movement of water and associated solute through the soil profiles (Beven and Germann 1982). Since flow through macropores is much faster than through the soil matrix, travel time for water and dissolved chemicals is directly affected by the number of macropores per unit area and also their continuity. Short travel time may not allow contaminants, such as pesticides, to be adsorbed on and into the soil surfaces and broken down by chemical and biological action. To obtain a better understanding of these soil-water processes, the characterization of the macropores (ie: areal distribution, size, shape, continuity, etc.) is essential.

Several researchers have used indirect approaches, such as the use of breakthrough curves or tension infiltrometers to study macroporosity. However, indirect approaches only provide qualitative information about soil porosity. Quantitative analysis of macroporosity provides a more comprehensive and systematic approach and is normally obtained by direct methods. Koppi and McBratney (1991), Moran and McBartney (1992), Singh and Kanwar (1991), and Vermel et al. (1993) used an impregnation and sectioning technique by intruding paraffin or epoxy resin into the soil profile and sectioning the soil sample with a mechanical saw. Other researchers such as Booltink and Bouma (1991), Logsdon (1995), Trojan and Linden (1992), and Wu et al. (1993) characterized flow patterns along macropores using dye tracers such as methylene blue. These two direct approaches have a common disadvantage, ie., the destruction of the soil sample before verifying that the dye, the paraffin, or the resin has been fully impregnated throughout the macropore structures of the soil profile.

In the early 1980s, CAT scan technology started to be used in non-medical fields and its great potential for non-destructive analyses was immediately recognized. In one of the first studies involving soil science, Petrovic et al. (1982) showed that CAT scanning was a promising tool for rapid determination of soil bulk density. They found that the mean bulk density in a soil core was linearly related to the core's mean X-ray attenuation coefficient. A year later, Hainsworth and Aylmore (1983) conducted experiments to examine the spatial changes in soil water content using CAT. They reported that computer assisted tomography was successful in monitoring the changes in soil water content and wrote: "CAT scanning presents an extremely exciting possibility for studies of soil-plant water relations ". Crestana et al. (1985) used CAT to observe the changes in X-ray attenuation coefficient

Table I: Studies using CAT scanning for the evaluation of pore structure of intact soil cores

Research Institution	Summary	Limitations	References
Department of Agricultural Engineering / Department of Radiology University of Minnesota, St. Paul , MN.	Macropores were detected with CAT scanning. By sectioning the soil core, the validity of CAT scanning was also verified. The number and size of macropores were approximately the same below a depth of 50 mm.	- Visual interpretation of scan images - Distance between scans varying from 10 to 50 mm - No consideration were given to the geometry and three-dimensional parameters of macropores	Warner et al. (1989)
Saskatchewan Institute of Pedology, University of Saskatchewan, Saskatoon, SK.	The soil macropore system and a compacted soil layer were analyzed using CAT scanning. The validity of CAT scanning was verified with impregnating techniques. A soil macroporosity of 15.7% was measured. The average area of a single macropore was found to be 20.4 mm^2.	- Small soil cores (160 mm in length) - Analysis of macropores performed on grey-scale images (not directly from the CAT scan raw data) - No consideration was given to the geometry and three-dimensional characterization of macropores	Grevers et al. (1989) Grevers and de Jong (1994)
Department of Agronomy and Department of Civil Engineering University of Missouri, Columbia, MO.	Undisturbed soil cores (76 mm diameter x 76 mm long) were scanned for evaluating the structural characteristics of soils (bulk density). Bulk density correlated well with the size and location of artificial macropores.	- Very small soil cores - No consideration was given to the geometry and three-dimensional parameters of macropores	Anderson et al. (1990) Peyton et al. (1992)
Department of Horticulture, Department of Agronomy, Department of Human Oncology, and Department of Radiology, University of Wisconsin, Madison, WI.	Macropore structures were reconstructed and visualized in 3D from CAT scan data.	- This study neither quantified nor characterized the 2D or 3D geometry of macropores.	Hanson et al. (1991)
Biology and Agricultural Engineering Department, Department of Crop and Soil Science, and the Institute of Ecology, University of Georgia, Athens, GA.	A theory for non-destructive determination of conductivity in soil cores (150 mm diameter x 350 mm long) in terms of the Poiseuille-Carman equation was evaluated. It was found that the number of macropores decreases with depth.	- Small soil cores - 50 mm distance between scans - No consideration was given to the three-dimensional parameters of macropores	Tollner et al. (1995)
School of Engineering (University of Guelph) and Imaging Research Laboratory (Robarts Research Institute), Guelph, ON.	A CT scanner was used to estimate the overall macroporosity of six soil columns. They reported a decrease in macroporosity with depth and found a greater variability closer to the surface.	- Small soil cores, 90 mm diameter x 200 mm long - Distance between scans was 20 mm - No consideration was given to geometrical characterization and three-dimensional parameters of soil macropores	Asare et al. (1995)

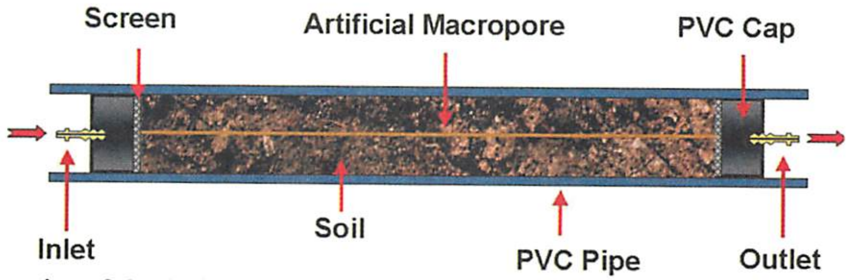

Fig. 1. Schematic illustration of the design of the soil column with the artificial macropore.

with time as a wetting front passed through a homogeneous soil core. They demonstrated the ability of scanners to detect water movement in soil and concluded that CAT scanning was opening new possibilities for non-destructive measurement of spatial and dynamic water contents. They also developed a CAT miniscanner for field analysis (Crestana et al. 1986). Using small homogenized soil cores, Anderson et al. (1988) showed that the relationship between volume fraction of solids in cores and mean X-ray attenuation was linear and found the CAT approach to be a powerful tool for soil research. Jenssen and Heyerdahl (1988) applied CAT scanning to study the packing arrangement and density of soil columns used in experiments concerning water transport and wastewater purification. They stated that CAT scanning "offers fascinating possibilities in the field of soil science".

The above studies clearly indicate that CAT scanning is a valuable tool for investigating soil-water processes. Other investigators such as Phogat and Aylmore (1989) have also demonstrated its potential for determination of soil water content and bulk density.

However, all of the above studies were performed using small cores that had been uniformly packed with sieved and homogenized soils. Therefore, these studies did not evaluate soil structures in their native field conditions.

Warner et al. (1989) are among the first researchers to have used CAT techniques for characterizing the spatial distribution of soil macropores of undisturbed soil cores. The feasibility of CAT scanning for macropore characterization was assessed by physically sectioning the soil column along the scan plane in order to compare features of scan images with the physical section of the core. Warner et al. (1989) reported that "the CAT scan process is a promising non-destructive method for the characterization of macropores in soil". However, the scans were examined and interpreted visually. They pointed out the need to develop a comprehensive algorithm to automate the interpretation of images produced by the CAT scanner. Moreover, the distance between consecutive scans in their study varied from 10 to 50 mm, leaving a big gap of "unexplored" soil. These gaps can cause a major problem in the interpretation of the results since continuity and tortuosity of macropores cannot be assessed.

Grevers et al. (1989) also investigated a soil macropore system by comparing images from CAT scanning with images obtained by physically sectioning the soil core. They found that the results of the CAT scan images compared well with the features observed in the sections of the soil columns. In their study, the length of the soil cores was limited to 160 mm. Thus, their investigation was limited to a small region of the vadose zone.

Following the pioneering work of Grevers et al. (1989) and Warner et al. (1989), several researchers examined, in greater detail, the use of CAT scanning for the characterization of soil macropores in intact soil cores. Table I provides an annotated reference list of the research work on CAT scanning for describing soil macroporosity in undisturbed soil columns. Up to now, it can be stated that the application of CAT scanning offers a very accurate and repeatable way to bypass the resin impregnation and other physical slicing operations in the standard optical approach to perform a pore characterization analysis. However, CAT has not been used to its full potential for the quantification of soil macropores and investigation of preferential flow processes. In most studies, the sizes of undisturbed soil cores were too small and the distances between consecutive scans were too large to generate accurate and complete characterization of soil macropores.

Some recent studies, like Asare et al. (1995), have used CAT scanning to investigate soil macropores. However, their study was limited to the variations of macroporosity in the A

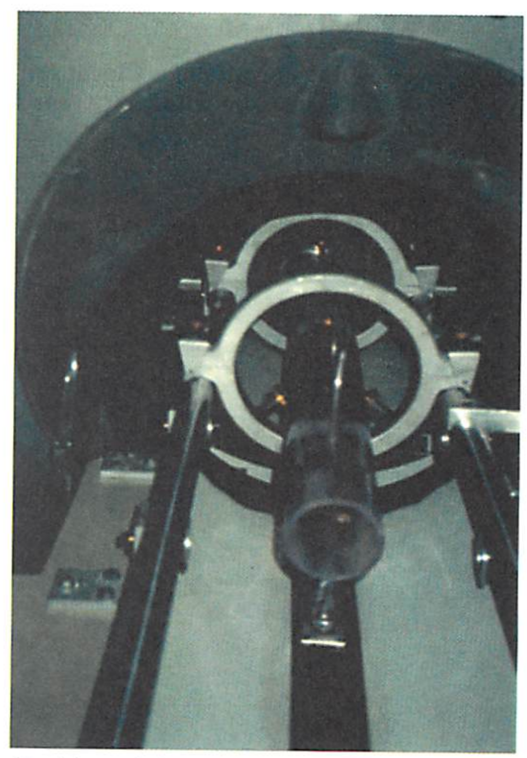

Fig. 2. Position of the soil core in the CAT scanner.

and B horizons. Their relatively small soil columns (200 mm x 90 mm) were scanned every 20 mm, leaving a big gap of unknown information between two consecutive scans. Moreover, in their work, consideration was not given to the number of macropores, their size, position, and geometry. In addition, three-dimensional parameters, such as tortuosity, connectivity, etc. were not quantified.

Imagery capabilities of most CAT scanners used in soil studies have been limited to two-dimensional serial scans. Very little work has been done to characterize the macroporosity of intact soil cores in terms of their three-dimensional parameters. Tollner et al. (1995) pointed out the need for additional research to investigate reliable approaches for computing tortuosity and connectivity of soil macropores. Imaging in three-dimensions and quantification of three-dimensional parameters of soil macroporosity are critical in order to accurately correlate soil pore structure with preferential flow phenomena and much additional work is needed in this area (Hanson et al. 1991).

We are currently investigating macroporosity and modeling preferential flow processes in four large undisturbed soil columns (800 mm x 77 mm) using computer assisted tomography with a X-ray based scanner. In this study, each soil column was scanned in 240 positions leaving no gap of information between two consecutive scans. Computer programs were developed in PV-WAVE language for systematic quantification and visualization of soil macroporosity directly from CAT scan data. Some of these computer algorithms are presented in this paper. The visualization part of this work enabled us to generate 3D views of the structure of macropores to an unprecedented level.

MATERIALS AND METHODS

Soil columns

In July 1995, four undisturbed soil columns, 800 mm long x 77 mm diameter, were taken from a field site at the Macdonald Campus of McGill University in Ste-Anne-de-Bellevue, QC. The land slope was less than one percent. The columns were extracted from an uncultivated field border that had been covered for many years with a combination of quack grass (*Elytrigia repens*), white clover (*Trifolium repens*) and wild oat (*Avena fatua*). Periodic mowing during the summer was the only cultural practice. The soil cores were obtained by driving a polyvinyl chloride (PVC) pipe into the soil with a backhoe. The lower end of the PVC pipe was shaped to a thin cutting edge in order to reduce the compaction inside the column and to facilitate the insertion of pipes into the soil. After the extraction of the columns, the cutting edge was removed, allowing the end of the PVC pipe to be sealed with a PVC cap. The soil columns were extracted during a period when the soil moisture was near field capacity. Between the time of excavation and the time of scanning, the cores were free to drain through a small outlet located at the bottom of the PVC pipes. Change in moisture content due to evaporation was minimal, since both ends of the columns were sealed to prevent any soil loss during transportation. One of the soil columns was drilled from top to bottom to verify the ability of the CAT scanner to portray the size and the location of a known pore. This artificial macropore consisted of a polyethylene tube of 1 mm in outer diameter (Fig. 1).

The soil where the soil columns were extracted is of the Chicot series. The Chicot soils are developed from sandy materials over a calcareous till and as a result they are generally well drained (Lajoie and Baril 1954). They usually contain a high percentage of fine sandy loam. The soil properties of the soil profile were determined by taking small

Table II: Selected Soil Properties of a Chicot soil under a combination of quack grass (*Elytrigia repens*), white clover (*Trifolium repens*) and wild oat (*Avena fatua*)

Depth (m)	Bulk density (Mg/m^3)	ρ_g[1] (Mg/m^3)	ω[2] (%)	Clay (%)	Silt (%)	Sand (%)	OM[3]	CEC[4]	pH	Description
0.0-0.15	1.36	2.51	23.9	6	12	82				Dark brown with fine crumb structures – slightly firm
0.15-0.30	1.27	2.52	24.7	5.5	12.5	82	3.96	9.66	6.32	
0.30-0.45	1.30	2.59	24.2	7	9	84				
0.45-0.60	1.30	2.60	21.5	5	8	87				Brown to yellowish brown – compact layer with occasional rocks presence of earthworm channels
0.60-0.75	1.46	2.64	11.8	8	8	84	1.20	8.01	6.01	Brown to greyish brown -gravely layer with a significant increase in clay content – very compact
0.75-0.90	1.64	2.59	14.2	14.5	8.5	77				

[1] Mineral grain density
[2] Gravimetric water content at field capacity
[3] Organic matter content
[4] Cation Exchange Capacity (Cmol/kg)

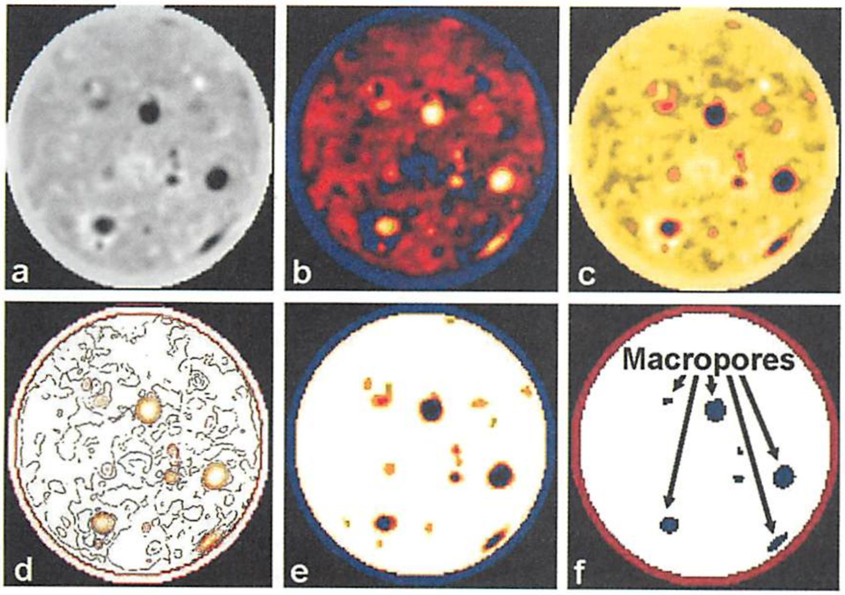

Fig. 3. Cross-sectional images; (a), (b) and (c) contrast enhancement using different color tables, (d) contour map, (e) partial threshold and (f) total threshold of the soil macropores.

threshold to isolate soil macropores. To enhance or mask portions of the image, a binary threshold was used for better detection of soil macropores. The program was used extensively for the visualization of cross-sectional images and the examination of shape, size, and distribution of macropores. Some of these cross-sectional images are presented in Fig. 3.

Longitudinal views are useful for the visualization of the distribution of low and high density areas along the length of the soil column. To generate longitudinal views, another program in PV-WAVE (Longi_mak.pro) was developed. This program stacks up 240 sections, one on top of the other, and "cuts" through a vertical plane to extract a vertical cross-sectional slice from the three-dimensional block of data. The position of the plane that bisects the volume of data is determined using a fixed pixel depth. For each column, 115 longitudinal images can be generated in the x-direction as well as in the y-direction. Figure 4 displays longitudinal views of the four soil columns, using a pixel depth in the x-direction of 50 (middle of the columns).

In hospitals, three-dimensional imagery has recently been possible with the aid of powerful stereotactic radiosurgery computer programs (Hanson et al.1991). However, these softwares are very expensive and not offered on typical medical scanners (Aylmore 1993). Since 3D imaging is critical in order to accurately correlate soil pore structure and space with flow processes occurring in the soil, it was decided to develop our own three-dimensional reconstructive methodology. Three programs in PV-WAVE were developed to generate three-dimensional models of macropores, based entirely on the CAT scan data. These three algorithms permit a three-dimensional image to be reconstructed from multiple contiguous scans. The first program (Make3D.pro) isolates macropores in 2D matrices, crunches the values of each pixel to a range of 0-255, and combines them into a 3D ASCII array. The second program (Conv_binary.pro) converts the 3D ASCII array into Binary I/O format. The Binary I/O format is the simplest and most efficient form of I/O. Images and large data sets are usually stored and manipulated using Binary I/O in order to minimize the processing load on the machine. The third program (Rview.pro) produces a list of vertices and polygons that describe the three-dimensional surface of macropores. Each voxel is visited to find polygons formed by the macropores. The polygons are then combined and rendered to reconstruct an exact three-dimensional representation of the interconnected network of soil pores and cavities. The reconstructed image allows the visualization of soil macropores as never seen before (Fig. 5). Several macropores are displayed as vertical descending structures. It should be noted that the artificial macropore in column 4 is clearly visible.

Quantification of soil macroporosity

The quantification of soil macropores seeks to identify inher-

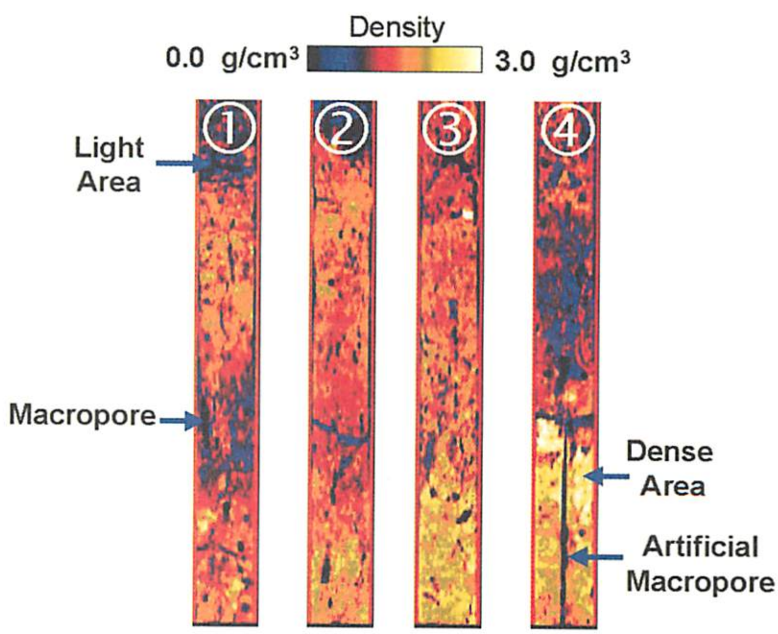

Fig. 4. Longitudinal views of the four soil columns.

samples from five locations at the field plot. The soil of this site was predominantly a loamy sand with an A horizon thickness of around 0.4 m. A summary of the results of soil analysis is presented in Table II. For determination of soil bulk density, percentage of clay, silt, and sand, and gravimetric water content, the reader is referred to Mehuys (1995). For determination of particle density and chemical analysis of soil, an X-ray spectrometer was used, following the method given by Jones (1982). The determination of organic matter was achieved by following the methodology given by Nelson and Sommers (1982). For cation exchange capacity and pH, the reader is referred to Hendershot et al. (1993a, 1993b).

Computer tomography process

Each of the four columns were scanned separately using an EMI CAT5005 full body scanner. In turn, each column was carefully placed horizontally in the CAT unit so that the X-ray beam would intersect the soil column perpendicular to its longitudinal axis (Fig. 2). During the computer tomography process, an X-ray source and an array of detectors rotate in synchrony around the column. A multiple set of data is generated from a number of views around a section of the core. More precisely, during a scan with the EMI CAT5005, the scanning assembly rotates in incremental steps of ten degrees around the core. This sequential rotation is repeated for 180 degrees to collect sufficient data to reconstruct a single slice. The X-ray attenuations obtained from the different angular positions are combined to generate the cells or pixels (picture element) of a 320 x 320 element matrix. Each individual pixel represents a specific CTN value (Computer Tomography Number) or a specific X-ray attenuation coefficient, normalized with respect to water. The CTNs constitute the standard output of a CAT scanner (CAT scan raw data) and are usually expressed in Hounsfield Units (HU). In this study, the CAT scan system parameters were set to 140 peak kV and 28 mA. A total of 240 sections or scans were obtained for each column in order to leave no gap between two consecutive scans. For each scan, the volume element size, often referred to as voxel, was 0.75 by 0.75 by 3.0 mm.

Matrix conversion and selection of region of interest

Each scan was recorded on a magnetic tape and transferred to a UNIX workstation and to a Pentium 133 MHz computer for further data manipulation. Although expressed in HU, a CTN value is a dimensionless quantity. The CTN for water is roughly 0 and it is -420 for air. The CTN values or X-ray attenuation coefficients are a function of the electron density (bulk density) and atomic number of the material. It has been previously demonstrated that the CTNs are linearly related to the bulk density of the soil (Anderson et al. 1988). The soil columns were mounted inside a core holder assembly made of a hollow Plexiglas annulus partitioned into four chambers filled with two liquids. Water and oil were used as reference materials. By plotting CTNs versus the bulk density of reference materials and using a simple linear regression, one can easily derive a calibration curve that relates bulk density to the X-ray attenuation coefficient of the scanned material. A FORTRAN program (Convert.f) was developed to compute the calibration line of each scan. Once the linear calibration equations have been established, a computer algorithm transforms CTN arrays into matrixes of bulk density. Part of the algorithm also allows the computation of porosity distribution of the soil. When the minerals constituting the soil particles have been identified, the porosity of each individual pixel was estimated from (Kantzas1990):

$$\phi = \frac{\rho_g - \rho_b}{\rho_g - \rho_f} \quad (1)$$

where

ϕ = porosity of the volume element,

ρ_g = grain density (density of the mineral making up the solid portion of the soil matrix),

ρ_b = bulk density, and

ρ_f = fluid density.

The fluid density in this case is the density of air.

An additional algorithm was added to the program for the selection of a region of interest (ROI). Only part of the 320 x 320 matrices is actually used for the investigation of soil macroporosity. The resulting matrix requires only 96 kilobytes of disk space and is composed of an array of 115 x 115 elements.

Selection of programming language

Presumably, any high level programming language, such as FORTRAN, could have been used for post-processing and manipulation of the two-dimensional matrices. FORTRAN is commonly used in problems requiring intensive computations. Unfortunately, the imaging capabilities of FORTRAN are poor. The PV-WAVE language is a comprehensive programming environment that integrates state-of-the-art numerical and graphical analyse. This programming language is widely used for analyzing and visualizing technical data in many fields, such as medical imaging, remote sensing, and engineering. PV-WAVE is an ideal tool for working with arrays, such as the CAT scan data, because of its array-oriented operators and its ability to display and process data in both ASCII and Binary I/O format. Therefore, PV-WAVE was chosen as the programming language to be used for this study. Another reason was PV-WAVE's ability to be used under both UNIX platform and PC environment.

Visualization of soil macroporosity

Visual inspection of bulk density and porosity matrices is an important step towards the understanding and analysis of the complex structure macropore. In this section, various ways of visualizing soil macropores are presented.

An interactive algorithm (Jofran.pro) was developed in PV-WAVE for comprehensive inspections of the bulk density and porosity matrices and creation of cross-sectional images. To generate images, the program converts ASCII matrices into BINARY format. Each pixel value is scaled between 0-255 to form the image. In this context, an image is a two-dimensional array of pixels for which each element is attributed to a color, depending on its value. This program was specially designed to allow: 1) selection of different color tables for contrast enhancement, 2) continuous mapping, 3) contour mapping, 4) region of interest examination (with the determination of summary statistics), 5) estimation of feature coordinates, 6) GUI (graphical-user-interface)

Fig. 5. Three-dimensional reconstruction of soil macropores of the four soil columns. The artificial macropore can be obseved in column 4.

ent macropore characteristics, such as their number, size, and geometry. These characteristics are used to describe macropores or the attributes of macropores prior to the subsequent task of classification and modeling. A program (Macro.pro) was written to recognize, extract and quantify the features of interest in each of the two-dimensional arrays. This comprehensive program provides a variety of measures of soil macropores, such as the number of macropores per scan, surface area of each macropore, equivalent cylindrical diameter, perimeter, circularity, and rectangularity. The size of the macropores is usually described in terms of its surface area ($A_{cross\ section}$) and its perimeter (P). A more intuitive indicator of macropore size is the equivalent cylindrical diameter (d_{eq}) of the pore. It is usually derived from the surface area as:

$$d_{eq} = \sqrt{\frac{4A_{cross\ section}}{\pi}} \qquad (2)$$

The shape of the macropore is generally characterized by computing its circularity (C) and rectangularity (R). The circularity is defined as the ratio of the perimeter of the macropore over the circumference of a circle, having a diameter equal to the equivalent diameter of the macropore (Perret et al. 1996). It can be written as:

$$C = \frac{P}{d_{eq}\,\pi} \qquad (3)$$

Since the circumference is the smallest closed line that embraces a two-dimensional figure, circularity can never be less than one. Circularity value of one implies that the macropore is circular. A circularity much greater than one indicates that the macropore is elliptical. Rectangularity is given by the area of the macropore divided by the area of a bounding box, formed around the macropore (A_{box}) (Tollner et al. 1995), and is written in mathematical terms as:

$$R = \frac{A_{cross\ section}}{A_{box}} \qquad (4)$$

The rectangularity can never exceed one. Rectangularity close to one implies that the macropore tends to be rectangular in shape.

For each column, the algorithm examines more than 310,000 data values in order to characterize macroporosity. The first task accomplished by the program is to partition the two-dimensional arrays into regions of 1 for the pores and 0 for the soil matrix. The pores contain either water or air (i.e., density less than 1). Thus, by applying a threshold on all the pixels in the bulk density matrices having a value lower than one, the pore can be isolated (Fig. 6). This process is called segmentation. Once the two-dimensional matrices have been transformed into 0 and 1 elements, the algorithm must recognize each individual pore, registered as a set of contiguous 1's. Two matrix elements having a value of 1 are said to be part of the same pore if they are sharing a common side. In other words, to be part of the same pore, a pixel needs to have a value of 1 and to be located in one of the four nearest neighbour locations of the other pixel. In a single pass of the two-dimensional array, our algorithm recognizes and regroups pixels belonging to the same pore. This part of the program is referred to as the clustering algorithm (Fig. 7). A subroutine in the clustering algorithm assesses the number of pixels, perimeter, and rectangularity of the pore. Some of the pores are too small to be classified in the macropore category. If the equivalent diameter of the pore is less than 1 mm, then the pore is removed from the two-dimensional matrix by resetting each of its pixels to 0. This simple process is called filtering. After filtering, all macropore attributes are computed. The program can be used either for one section or for all the 240 sections of a soil column. All macropore attributes are stored in an ASCII file for further analysis on a worksheet.

RESULTS AND DISCUSSION

Variations in bulk density and total porosity were investigated as the first basic properties of the soil. As noted earlier, the density matrix is based on the X-ray attenuation coefficient of each voxel of the scan. Each voxel contains a mixture of solid particles (mineral grains, organic matter), air, and water. Therefore, the X-ray attenuation coefficient and hence the bulk density matrix is affected by the water content of the soil at the time of scanning. In other words, the density matrices represent the wet bulk density of soil. It was assumed that the soil columns were at field capacity during the

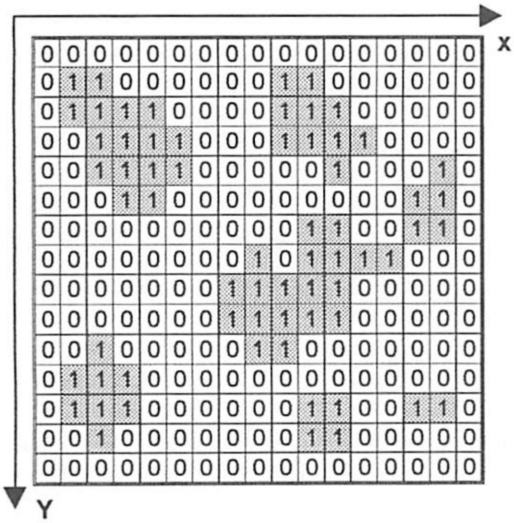

Figure 6 - Partial view of the 2D array after segmentation.

Fig. 6. Partial view of the 2D array after segmentation.

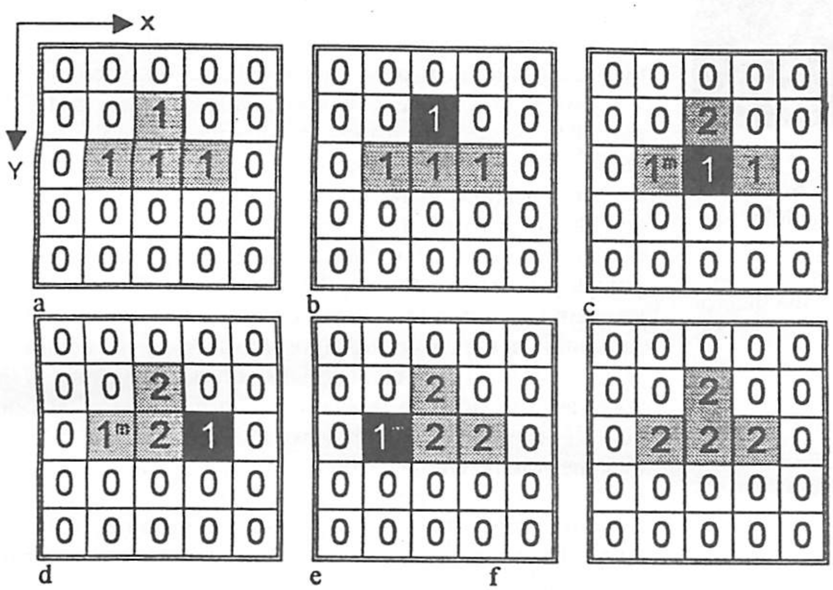

Fig. 7. Illustration of the clustering algorithm. (a) Initial matrix. (b) The first pixel is located and the four nearest neighbors are checked for values of 1. (c) The visited pixel changed to a value different than 1 (2 in this case) and the investigation moves to the neighbor having a value of 1 (if two or more neighbors have a value of 1, the algorithm puts them in "memory"). The four new neighbors are evaluated. Two neighboring pixels have a value of 1, therefore, one of them is put in memory (denoted by 1^m). (d) The previous pixel is changed to 2. None of the four neighboring pixels has a value of 1, thus, the algorithm moves to the pixel in memory. (e) A value 2 is substituted in the pixels and the new neighbors are investigated. None have a value of 1 previous and no pixel in memory can be recalled. (f) The evaluation of this pore is completed.

CAT scan process. Gravimetric moisture content of the soil, at field capacity, was estimated at 20%. With the gravimetric moisture content known, the dry bulk density was calculated as:

$$\rho_{bdry} = \frac{\rho_{bwet}}{1+\omega} \quad (5)$$

where:

ρ_{bdry} = dry bulk density (Mg/m^3),
ρ_{bwet} = wet bullk density (Mg/m^3), and
ω = gravimetric moisture content.

With this formula, the dry bulk density was calculated and averaged for every section of the soil columns. In addition, the total porosity of the soil was evaluated by:

$$\phi = 1 - \frac{\rho_{bwet}}{1+\omega} \quad (6)$$

where:

ϕ = total porosity, and
ρ_g = mineral grain density (Mg/m^3).

The mineral grain density, also known as the soil particle density, was estimated by X-ray Fluorescence with a PW240 spectrometer. It was measured at six depths and the average value for the soil profile was found to be 2.58 Mg/m^3. Figure 8 shows the variations of the dry bulk density and the total porosity with respect to depth, for each soil column. In 1995, the soil columns were scanned at field capacity (gravimetric moisture content ≈ 20.2%) whereas, in 1996, the soil was dry during scanning. Therefore, higher bulk density and lower porosity are expected for 1995. Figure 8 confirms this supposition.

The bulk density of the soil ranges from approximately 1.2 to 1.89 Mg/m^3 while the minimal and maximal value for total porosity is 53.7 and 27.5%, respectively. The field site, from which the soil columns were extracted, is used as passageway for machinery during the summer activities. Marshall and Holmes (1988) mentioned that the bulk density of a sandy loam soil, which has been compacted by regular traffic, could reach 1.90 Mg/m^3 with porosity values around 28%. Thus, the results presented in Fig. 8 appropriately describe soil conditions prevalent at the field site. The density tends to increase with depth. This observation may be attributed to an increase in the compaction of soil particles and a decrease in the organic matter content with respect to distance from the soil surface.

Spatial resolution of the image, as determined by the scanner and the reconstruction algorithm, is 0.75 mm. If the boundary of a pore falls in the middle of a pixel, the scanner will generate a CTN value that is an

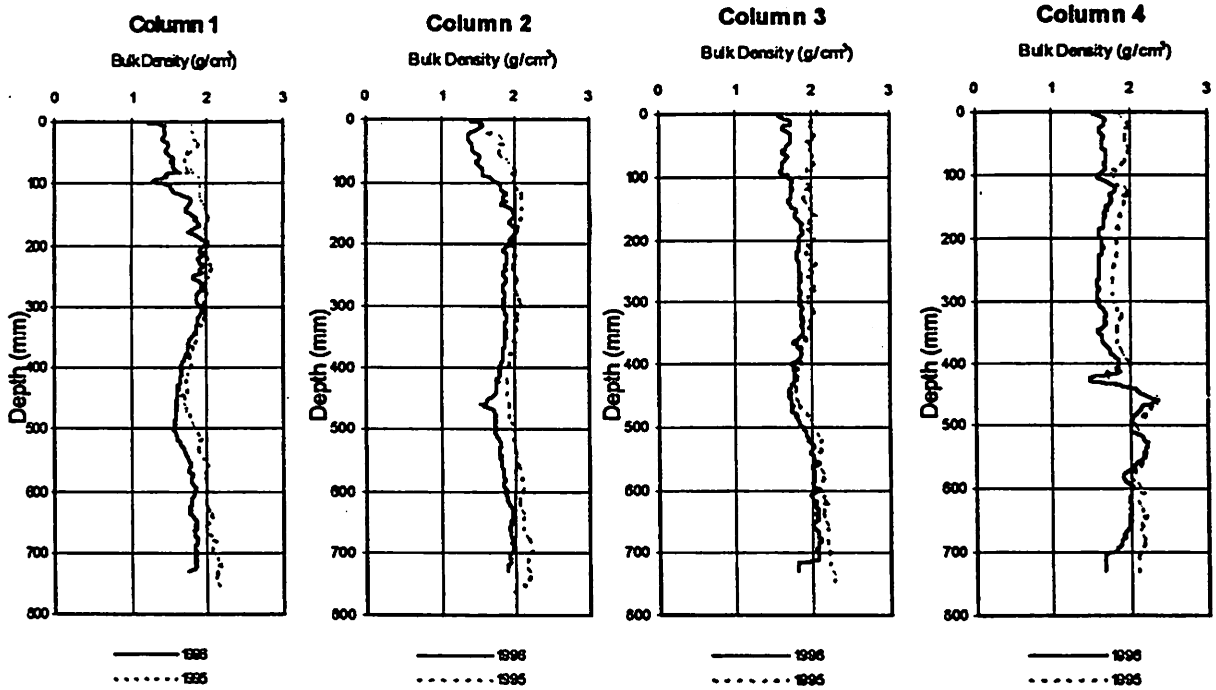

Fig. 8. Dry bulk density changes with depth of the soil profile.

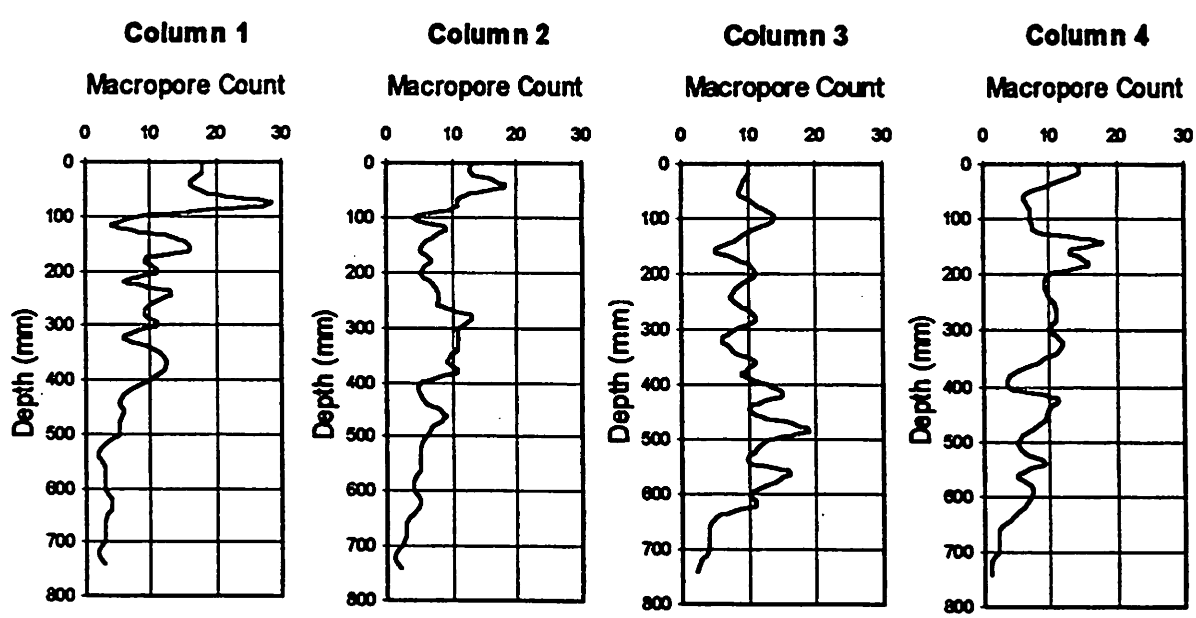

Fig. 9. Number of macropores with respect to depth.

average of the attenuation of the soil matrix and air. The possibility that a pore of approximately 0.75 by 0.75 mm coincides with a pixel is very small. Thus, a pore must be significantly larger that 0.75 mm to enable detection and accurate identification. Pores greater than 1.0 mm in diameter can be easily identified and characterized. This category of pore was defined as macropores by Luxmoore et al. (1990). However, it should be mentioned that the geometry of soil pores is rarely circular and, therefore, the concept of diameter is no longer adequate. Consequently, the term equivalent cylindrical diameter is used to describe the size of non-circular/circular pores. For every section of the soil columns, the number of pores having an equivalent cylindrical diameter greater than or equal to 1 mm (macropores) was evaluated. The results are shown in Fig. 9. In general, the number of macropores decreases with depth. The decrease in the number of macropores is due to a decrease in biological activity. The number of macropores close to the soil surface may be affected by plant roots and species of oligochaete (earthworms, potworms, bristleworms, etc.) that are not present deeper into the soil profile. A high biological activity will result in the formation of more macropores near the soil

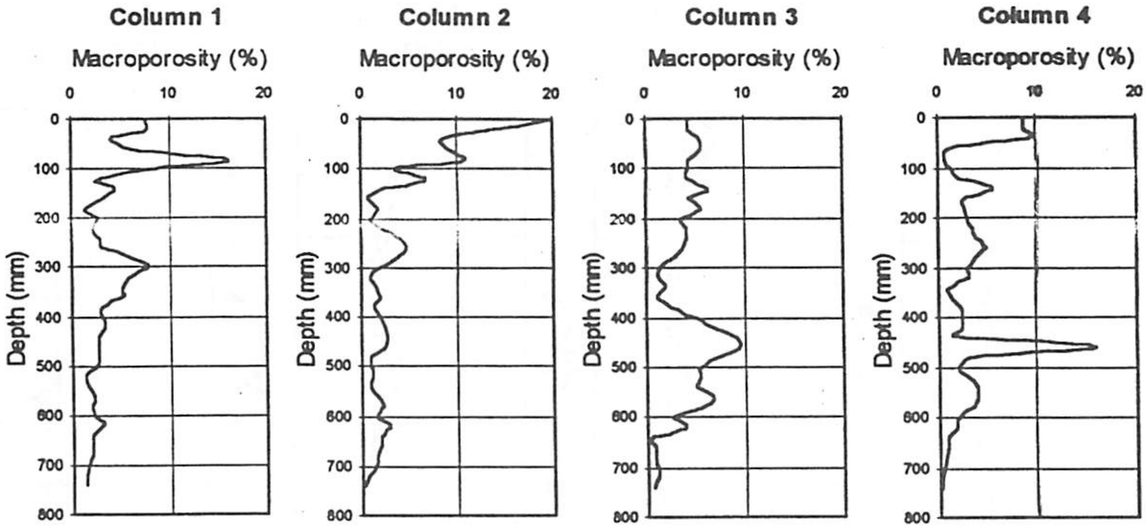

Fig. 10. Areal distribution of soil macropores wih respect to depth.

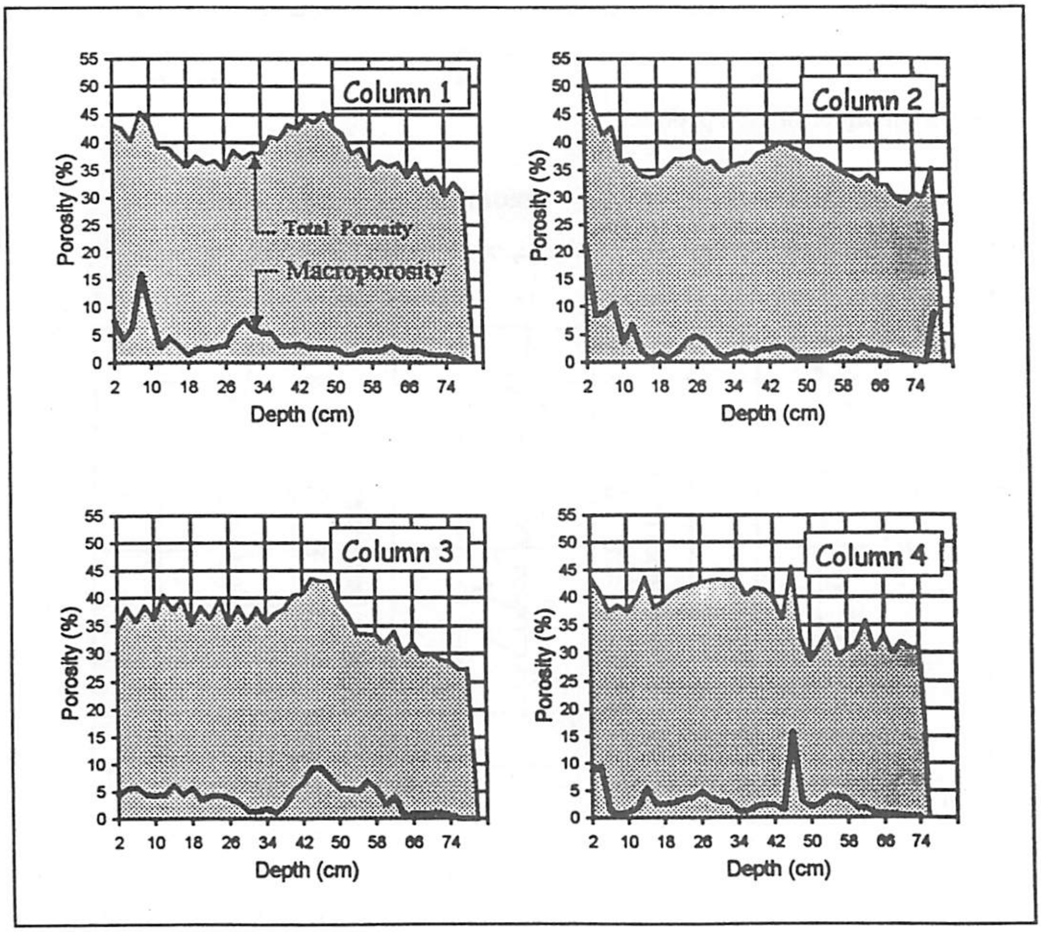

Fig. 11. Relative contribution of soil macroporosity with respect to depth.

surface. However, in column 3, this trend is not as obvious as it is for the other columns. During transportation, the soil from the middle of column 3 may have been accidentally loosened and could have led to the jumbled macropore count observed in the column.

The areal distribution of the soil macropores was also investigated by dividing the sum of all pixels belonging to soil macropores by the total number of pixels in the section. In other words, the areal distribution of the soil macropores, sometimes referred to as macroporosity, is given by the ratio of the surface area occupied by macropores divided by the total surface area of the section. The areal distribution was evaluated for every depth and is presented in Fig. 10. Since the biological activity close to the soil surface is more intense, one should anticipate a lower macroporosity deeper in the soil profile. As expected, macroporosity decreases with depth. A comparison of the total porosity to the macroporosity of the soil can indicate the relative contribution of soil macropores to the porosity of the porous medium (Fig. 11). Figure 11 shows similar trends for the total porosity and for the macroporosity of soil columns. Although macroporosity represents a minor portion of the soil porosity, it clearly affects the behaviour of the total porosity of the soil. White (1985) reported that soil macropores comprise a small percentage of the total porosity (1 to 5%). Edwards et al. (1990) observed

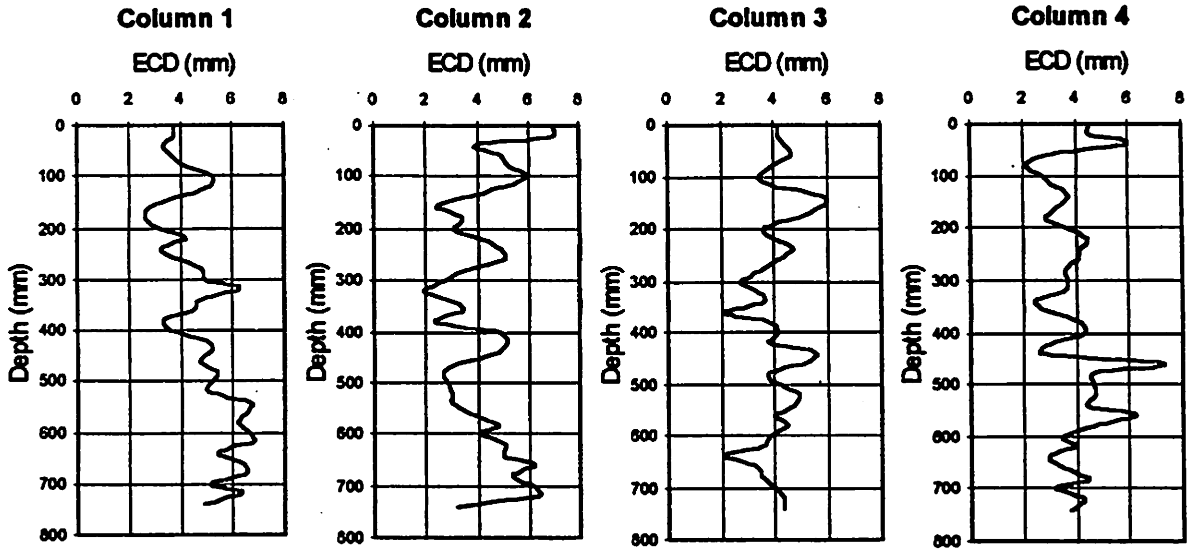

Fig. 12. Average equivalent diameter of the soil macropores with respect to depth.

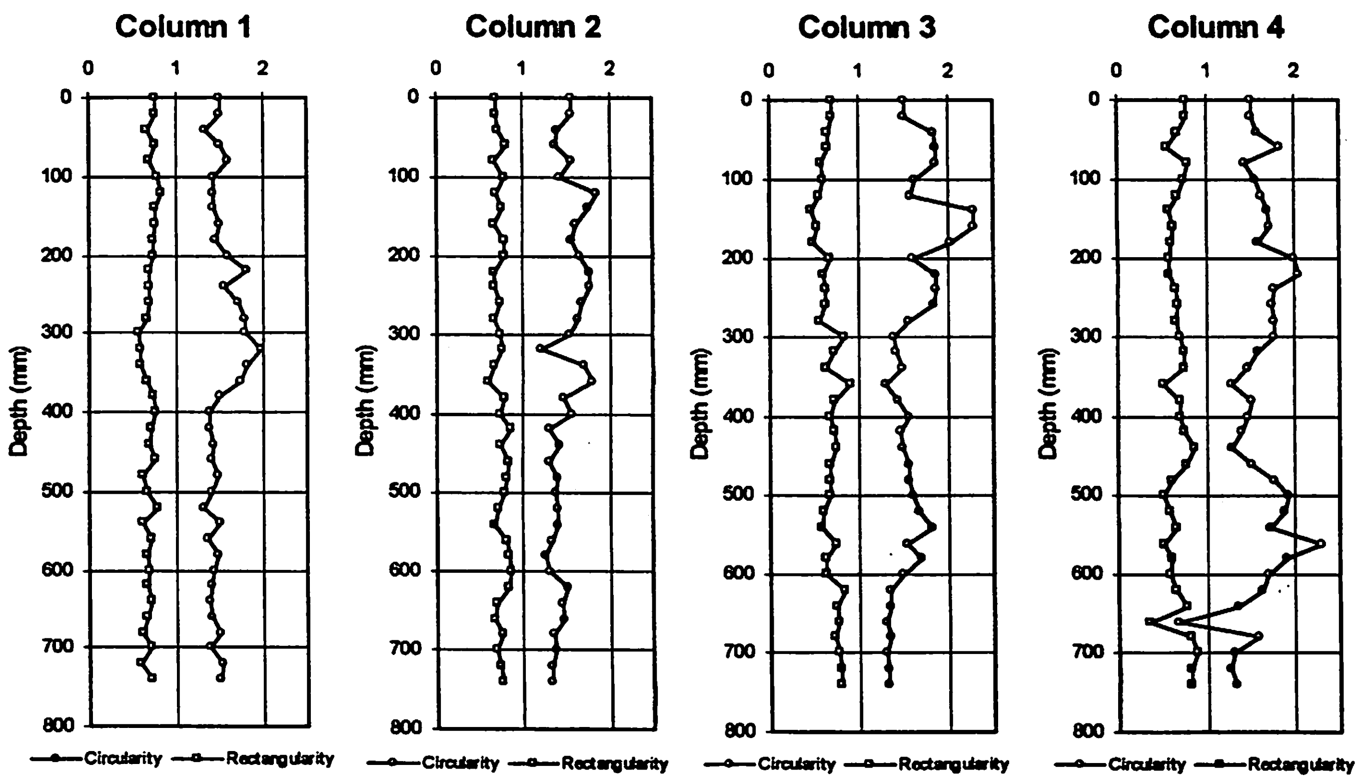

Fig. 13. Average circularity and rectangularity of soil macropores with respect to depth.

macroporosity having a range from 0.4 to 3.8%. However, these figures were estimated with infiltration techniques and thus some dead-end macropores, which do not participate in carrying water flux, were not considered.

CAT scanning provides a more systematic approach for estimating macroporosity since all soil cavities are taken into consideration. Thus, higher values of macroporosity are obtained using CAT scanning. Asare et al. (1995), for instance, have reported values of macroporosity ranging from 13.8 to 36.1%. Therefore, the results obtained in our study seem to be reasonable.

As mentioned earlier, the size of the macropores may be inferred from their equivalent diameter. The average equivalent diameter was computed for each section of soil in order to investigate changes in the size of macropores with depth. The results are presented in Fig.12. The assumption is that the size of macropores changes with depth, however, it is difficult to recognize a trend or a pattern in the fluctuations of the equivalent diameter. The presence of roots and arthropods, such as ants or beetles, close to the soil surface could have led to two distinct regions in the soil profile. However, the size of the macropores does not seem to be affected by depth. The geometry of a macropore may be investigated by estimating its circularity and rectangularity. Circularity is defined as the ratio of the perimeter of the macropore over the circumference of a circle having a diameter equal to the equivalent diameter of the macropore. Since the circumference is the smallest closed line that embraces a two dimensional figure, the circularity can never be lower than one. A circularity equal to one implies that the macropore is circular. A circularity much greater than one indicates that the macropore is elliptical. Rectangularity is given by the area of the macropore divided by the area of a bounding box, formed around the macropore. The rectangularity can never exceed one. A rectangularity close to one implies that the macropore tends to be rectangular in shape. The average circularity and rectangularity was calculated for every section of the soil column in order to examine the changes in the geometry of soil macropores with respect to depth (Fig. 13). The geometry of soil macropores seems to be independent on the distance from soil surface. Although the circularity and rectangularity fluctuate, there is no clear evidence of a tendency to increase or decrease with depth. It should be noted, however, that the rectangularity oscillates around 0.70. This means that the geometry of the macropores tends to occupy a rectangular surface at approximately 70%.

Although macropores are less numerous deeper into the soil profile, they tend to have the same size and geometry. This implies that the origin or mode of formation of macropores is approximately the same throughout the soil profile. In temperate regions, earthworms dominate the soil's invertebrate biomass (Curry 1994). The formation of burrows is a distinctive feature of earthworm activity. Normally, large species, such as *Lumbricus terrestris,* which can weigh more than 5g per worm, contribute substantially to the formation of long and continuous burrows. This species of earthworm has been observed in the soil columns used in this study. These earthworms usually make vertical burrows down to depths of 2 m or more (Edwards et al. 1990; Ehlers 1975). These channels have a diameter ranging from 1 to 12 mm with smooth walls cemented with mucus secretions. The burrowing species create permanent and empty channels, which tend to run in the vertical direction. Since these types of macropore are present both close to the soil surface and deeper into the soil profile and therefore, it is possible that, on average, the equivalent diameter, circularity, and rectangularity do not decrease nor increase with depth in our 0.72 m long soil columns.

SUMMARY AND CONCLUSIONS

The integration of computer programming in the PV-WAVE language, hardware, and medical imaging devices in soil studies gives us the ability to investigate the interconnected pore space of large undisturbed soil columns to an unprecedented level. With the development of computer programs in PV-WAVE, the analysis of soil macropores was performed directly on the CAT scan data. Pores larger or equal to 1.0 mm in equivalent diameter were readily detected, visualized, and quantified. The data generated by the CAT scan process was manipulated in order to accentuate different features of the soil. Soil macropores were isolated by thresholding certain values of the density matrices. This approach was utilized for each section of the soil columns in order to evaluate: the number of macropores, the surface area, the equivalent diameter, the circularity, and the rectangularity of each individual macropore. Both the number and the surface area occupied by soil macropores decrease with depth. It was also observed that the size of the macropores is not affected by the distance from the soil surface. Moreover, the geometry of the macropores is apparently not a function of the distance from the soil surface.

3D imaging is critical in order to accurately correlate soil pore structure and space with flow processes occurring in the soil. Programs in PV-WAVE were developed to visualize the complex three-dimensional network of interconnected pore space. These 3D reconstructions are unique.

Additional research is needed, particularly with respect to the continuity and tortuosity of the macropore. In the near future, geostatistics and fractal analysis will be used to complete the quantification of the soil macropores.

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