ASSESSMENT OF HYDRO-PHYSICAL PROPERTIES OF SOME CRUSTING SOILS IN FOUR DIFFERENT SOIL FORM AS REVEALED BY MICRO-FOCUS X-RAY COMPUTED TOMOGRAPHY IN LIMPOPO PROVINCE, SOUTH AFRICA.

BY

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A DISSERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURE (SOIL SCIENCE) AT THE UNIVERSITY OF VENDA

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DECLARATION

I, Khuthadzo Tendani Given Mpofu, hereby declare that this Dissertation for Master of Science (MSc) in Agriculture (Soil Science) with the topic “hydro-physical properties of some crusting soils in south Africa as revealed by x-ray micro-focus computed tomography” submitted to the Department of Soil Science, School of Agriculture, University of Venda has not been submitted previously for any degree at this or other University. It is original in design and in execution, and all reference material contained therein has been dully acknowledged.

Signature

Date: 24 MARCH 2020

DEDICATION

I dedicate this research work to University of Venda Soil Science Department for giving me opportunity to carry out the study. Also, my special family and supervisors who are always there encouraging and motivating me throughout the academic journey.

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ABSTRACT

Most of the available knowledge about soil structure degradation through crust formation is limited to two-dimensional geometry. However, soil is a natural three-dimension body. The objective of the study is to assess soil crusting and hydro physical properties in four different soil form by using X-ray Computed Tomography, Characterizing micro-morphometric of crusting soil's pore system, quantifying soil structure degradation through crusting development and visualizing hydro physical properties in all four-soil form. Micro X-ray Computed Tomography techniques can greatly add value to existing knowledge because they can reveal soil structure in three dimensions (3D). Undisturbed soil aggregates were obtained from two adjacent sampling locations namely Visibly Crusted (VC) and Not-Visibly Crusted (NVC). Four soil forms were studied in Limpopo province, South Africa at Vhembe Region under Thulamela and Collin Chabane local Municipality. Soil form studied are Dundee, located at (Tshamutoro village), Shortlands (Mukula Village), Hutton (University of Venda) and Glenrosa (Ha-Davhana village). The samples were scanned using Nikon XTH 225L micro-focus CT X-ray unit. The scans were reconstructed into three-dimensional volume data set of pore shapes, pore size and porosity among the soils using CT Pro software® and further analysed using VG Studio Max V3.0®. images were acquired after 30 minutes in each scan. The result of the study indicated that total porosity decreases with increase in depth, and the shape of the aggregates were dominated by regular pores that are susceptible to water erosion. Moreover, soil pores inform of mesopores, micropores, and macro pores were recorded using 3D images acquired .By visualizing hydro physical properties using images in 2D and 3D, it was possible to visualize arrangement of aggregates and their sizes helping to understand the erodibility of soil. In conclusion X-ray computed tomography is an effective tool to study the microstructure of soil aggregates.

Keywords: Pore Size; Pore shape; Particle Size Distribution; Porosity.

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LIST OF ABBREVIATIONS

µCT: Micro-focus computed tomography

Ct: Computer tomography

Dm: Deci-meters

GB: Gigabyte.

MIXRAD: Micro-focus X-ray Radiography and Tomography laboratory at Necsa.

MXCT: Micro-focus X-ray computed tomography.

NECSA: South African Nuclear Energy Corporation.

NVC: Not visibly crusted.

PVC: Polyvinyl chloride.

RIO: Region of Interest.

VC: Visibly crusted.

LIST OF FIGURES

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

Crusting is a major soil structural feature (Kokeh *et al*., 2017) that is formed by breaking down of soil aggregates. Large aggregates are less likely to form crusts compared to small ones (Bullard *et al*., 2017). Sjoblom (2016) described soil crust as “a thin layer (3-5 mm) of low porosity formed at the soil surface that develop by either biological or physical processes. Biological crust is formed due to biological organisms that are found in uppermost millimetres of soils. They are formed by interaction of soil particles and microorganisms such as cyanobacteria, green algae, fungi bacteria lichens and other cryptogams (Armenise *et al*., 2018). Physical crusts can either be structural or depositional. They are formed by action of water and wind on bare surface (Tang *et al*., 2017). Few studied have been conducted concerning micro analysis of soil aggregates, in recent publication. For example, Zhao *et al.* (2017) investigated the impact of natural re-vegetation on aggregate microstructure using synchrotron-based X-ray micro-computed tomography and image analysis and observed that aggregate water stability was higher after re-vegetation but did not differ significantly among abandoned sites. Armenise *et al*. (2018) studied soil crust using micro X-ray computed tomography (X-ray µCT) techniques and used the images to measure seal and crust thickness. The authors were able to develop and test a new imaging approach for quantifying seal/crust thickness under simulated rainfall at fine spatial and temporal scale. In general, the results demonstrated how surface condition of intensively cultivated soils can influence potential ability of soils to act as water reservoir.

Stability of soil aggregates is important in preventing soil degradation. The ability of soil to resist breakdown due to water impact reduces erosion (Nciizah and Wakindiki 2015). These authors reported that soil crusting is influenced by soil texture, wetting rate, antecedent moisture content, clay mineralogy, rainfall characteristics and soil organic matter.

Crusted soils are associated with reduction of water infiltration, increased erosion, mechanical impedance of seedling emergence, and reduced aeration (Nciizah, 2015). Pires *et al*. (2017) used X-ray computed tomography (x-ray CT) in three dimensions (3D) to analyse pore systems such as porosity, pore number, pore shape, and pore size distribution. Pore size distribution was reported as a factor that affect water infiltration and retention hence classified as a major hydro-physical property. Nevertheless, Rabot (2018), reported that soil structure can be determined in laboratory using direct methods such as bulk density, aggregate size distribution and stability. However, indirect methods such as mercury porosimetry, water retention curve and derived indicators, gas adsorption can be used. Hence, x-ray CT in 3D imaging technique directly measure soil hydro-physical properties such as porosity, pore size distribution, pore size, number, shape, length, size and bulk density.

Müller et al. (2017) compared traditional method of determining macro-porosity with visualizing images using X-ray computed tomography (3D), and concluded that linking these two techniques improved parameterizing macrospores' hydraulic properties and there is a need to apply such kind of skill in large scales and other soil types.

Micro-focus x- ray computed tomography “is a non-destructive imaging technique that evaluate the internal structure and composition of a specimen using X-ray absorption differences” (Sjoblom, 2016). X-ray CT has been applied to characterise soil physical properties and structure under different tillage practices including Asphalt mixture in form of cement analysis, particle movement in soil (Pires *et al.,* 2016; Pöhlitz *et al*., 2018; Tseng *et al*., 2018 and Müller *et al*., 2017; Grayling *et al*. 2018 and Huining *et al*. 2017). Most of the available knowledge about soil structure degradation through crust formation is limited to two-dimensional geometry although soil is a natural three-dimension body. Moreover, most data have been collected on disturbed samples, which may not be a fair representation of the natural phenomenon.

This study aimed to visualize 3D whole images of crusting soils and describe their hydro-physical properties using X-ray computed tomography (X-ray CT) images. Variation of visibly crusted (VC) soils and not visibly crusted soil (NVC) was considered with depth. A Morphometric characterization of crusting soils pore system was conducted to mimic natural soil body in the pores to analyse size of pores, shape and particle size distribution hence, to quantify soil structure degradation through crusting ;furthermore, to understand soil structure which is a prerequisite to effective soil use and management.

1.2 PROBLEM STATEMENT

Most of the available knowledge about soil structure degradation through crust formation is limited to two-dimensional geometry although soil is a natural three-dimension body. Moreover, most data have been collected on disturbed samples, which may not be a fair representation of the natural phenomenon. Therefore, more information or data available in soil science soil description have been collected from disturbed soil sample. The use of X-ray computed tomography for hydro-physical properties analysis in Limpopo is a challenge to agricultural community since it requires intensive input data both in 2D and 3D geometry. Hence, hydro physical properties of soil have significant impact on soil water balance as a result affecting plant available water content, crop growth, transpiration and crop yield.

1.3 JUSTIFICATION

A satisfactory understanding of the effect of soil crusting on the soil hydro-physical properties requires studies that mimic the natural environment as much as possible. Three dimensional digital models of the whole specimen can be obtained using X-ray µCT. A precise understanding of the soil structure is a perquisite to effective soil use and management. Effects of soil hydro-physical properties have a direct relations with plant growth and it is important in simulating crop growth. Understanding of soil physical properties in an area determines soils quality and its capability to serve the ecosystem. Knowledge about hydro-physical properties need to be improved to mitigate impacts of future land modifications and understanding soil functioning. Hence, understanding water retention and water movement in soils and water accessibility for plant uptake and growth. Although other factors like precipitation, temperature and climate can have effect on land, detailed analysis using x-ray computed tomography is significant to improve analysis of hydro physicals saving time and energy.

1.4 AIM AND OBJECTIVES

1.4.1 AIM

To assess soil crusting and hydro physical properties in four different soil form by using X-ray computed tomography in South Africa.

1.5 OBJECTIVES

1. To characterize micro-morphometric of crusting soils' pore system using x-ray computed tomography.
2. To quantify soil structure degradation through crusting.
3. To visualize soil hydraulic properties of four different soils.

1.6 HYPHOTHESES

1. Crust formation does not affect the morphometric characteristics of different soils.
2. Crust formation does not affect soil structure degradation in different soils.
3. Images of soil hydraulic properties using x-ray computed tomography will be limited to 2 dimensions (2D) only.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 NATURE OF CRUSTING SOILS

Many studies on crust development have been experimentally performed and reported Sjoblom, (2016). Tang *et al*. (2017) reported that "the study on soil crusts combining geoscience and biology has become a research focus area and leading edge in arid and semi-arid regions. However, the authors also reported that crust are distributed in arid and semi-arid regions. Hence, Nciizah (2015) reported that soil crust is only applied when soil is in dry state containing firm and brittle surface otherwise formed when heavy rainfall causes the consolidation of soil surface particles.

Soil crust are formed either by biological or physical processes. Biological crusts are formed by biological organisms (algae, lichens etc.) that bind particles together. Physical soil crusts are those crusts formed by raindrop impact caused by in situ breakdown of aggregates into fine particles (structural crusts) and translocation of fine particles (depositional crust) or away from (erosional crusts).

A study conducted by Sjoblom (2016) investigated the mechanical nature of crust formation due to raindrop impacts using experimental procedures and micro computed tomography. They concluded that Discrete Element Model 2D (DEM) simulation is more effective to replicate crust formation. Armenise *et al*. (2017) also adopted micro-computed tomography to measure soil seal and crust thickness under simulated rainfall. In addition, they developed a new procedure to quantify seal thickness.

Soil crust is reported to improve the resistance to wind erosion of underlying soils. However, reducing infiltration rate and splash erosion, increased surface runoff. Therefore, soils become resistant to erosion (Niu *et al.* 2017). The nature of crust formation is controlled by soil texture and soil structure is affected by amount, temporal distribution and intensity of rainfall (Tang et al. 2017).

2.2 SOIL HYDRO-PHYSICAL PROPERTIES

Rabot et al. (2018) describes soil aggregate as solid phase of soils. The authors reported that aggregates are viewed in three stages organized in hierarchy of soil solid phase. Primary particles (< 20 µm) are bound together into micro-aggregates (20- 250 µm) and bind to form macro aggregates (> 250 µm). In addition, they indicated that aggregate and macro aggregates formation can form around particulate organic matter, then micro aggregates are released upon breakdown of macro aggregates. Soil breaks into aggregates of higher order than the single grains called pedals and they are graded as strong, moderate or weak. Aggregate shape is described according several types of soil structure, among others, Angular blocky; Sub angular blocky; Granular; Platy; Prismatic or Columnar (Cuomo *et al*. 2017).

Surface of soil particles are assumed to be the walls of the pore space. Soil pore depend on size and they are classified as macropores; mesopores and micropores. They are divided into textural and arrangement of the soil primarily called textural pores and structural pores are bigger pores from biological activity formed by climate and management practices.

Soil porosity can be derived from bulk density with known particle density. Porosity can be determined using indirect methods such as Mercury porosimetry, water retention curve and derived indicators and gas adsorption. Direct methods include imaging technique such as X- ray computed tomography which measures porosity, pore size distribution and interfacial areas, number; length; shape and orientation pores which can be retrieved directly without assumption on pore shape (Pires *et al*. 2018).

A study by Pires *et al*. (2017) reported that pores of distinct size present a function in soil. Pores > 50 µm are classified as transmission pores, < 50 µm as residual + boning pores and pores between 0.5 µm and 50 µm are responsible for water retention. In addition, pore shapes were classified as equant (Eq); prolate (Pr); Oblate (Ob); Triaxial (Tr); planner (Pi); acicular (Ac); or acicular-planer (Ap). Pores are responsible for water drainage and solute flux processes. Zhao *et al*. (2017) classified soil pores in four groups: < 30 µm; 30-75 µm; 75-100 µm and >100 µm. However, Pires *et al*. (2017) classified pores as small (156-15600 μm^2); medium (15601-156000 μm^2) and large > 156000 μm^2. Rabot *et al.* (2018) reported that pores > 250 µm are responsible for water-stable aggregates; pores between 50-250 µm represent water stable micro-aggregates.

Bulk density is the indicator of soil structure. It is calculated as a ratio of dry mass solids to the undisturbed soil volume. It is calculated by using cores of known mass size, it can also be determined by excavation and clod methods. It is useful to estimate soil compaction and increase in bulk density decrease root length density, root diameter and root mass. Particle size distribution or texture is known to control water infiltration and retention.

Studies conducted by Müller *et al*. (2018) explored macro-porosity using X-ray computed tomography and concluded that soil visualization is a powerful tool for classifying soil pores. The authors used post-processed segmented images to view macro porosity density, the number of macropores in a unit of soil volume, total porosity, volume of macropores connected from the top to the bottom of the soil volume using Particle Analyzer plugin within BoneJ plugin. Aggregates are described in term of size; porosity; shape; colour; ease of breakup; present of tillage pan; depth of root penetration or earthworms (Jorbenadze *et al*.2017). Aggregate size distribution indicates the ability of soil to retain soil structure under actions of water and mechanical stress. In addition, it indicates the resistance of soil to erosive agents and protect organic matter quality. Yang *et al*. (2017). Particle size distribution depends on precipitation agent, flow hydraulic characteristics and slope gradient (Li *et al*. 2018).

2.3 ALTERNATIVE METHODS USED TO STUDY SOIL HYDRO-PHYSICAL PROPERTIES.

Pore space can be characterized using some laboratory technique and imaging techniques. Rabot *et al*. (2018) reported methods of measuring pore space in sample sizes of centimetres to decimetres, such methods include: Indirect methods, Mercury Porisimetry, Water retention curve and derived indicators, Gas adsorption and imaging techniques in laboratory.

Indirect methods of measuring pore space (porosity) use probe molecules to derive information about the pore size, volume, and for pore-solid surface area, as opposed to imaging techniques like X-ray computed tomography and neutron tomography, these methods are not spatially resolved and do not characterize the morphology and topology of the pore space (Rabot *et al*. 2018).

Mercury porisimetry method has been used in decades to characterize pore size distribution. The wide use of this method lies in the ability to use large range pore sizes that can be investigated in a single run usually about 3 nm to 500 µm. analysis of sample using porisimetry can be completed with few hours with the use of soil aggregates between about 2 to 6 cm^3 in size. The instruments are easily available, and repeatability of the method is good. Mercury is usually performed in its “intrusion” mode. Non-wetting fluid mercury is forced to intrude a soil sample by applying known increasing pressure to fill pore sizes. Hence, “extrusion” methods can be used even though not rarely done in soil science by decreasing the applied pressure, however, detailed method can be obtained in (Van Brakel *et al.* 1981). The use of extrusion method has limitation in impending clear interpretation of the results. For example, in the case of the “ink-bottle”, the actual pore size is not measured completely. Pore sizes measured using “extrusion” method are usually smaller than those measured by imaging method, pores disconnected from the external surface of the investigated aggregates and the derived total porosity is thus underestimated. Contact of mercury with soil surface is often unknown, Also it requires a dried sample for analysis.

Water retention curve has been used to study the pore size distribution. Its indicators include porosity, macro porosity, micro-porosity and mesopores. Sample size can range from hundred cm^3 to dm^3 and pore size observed can be between 0.2 to 300 µm. Nonetheless, the analysis commonly takes days to weeks to complete, the cost of the analysis is medium. limitations of water retention curve can be the assumption of non-connected cylindrical pores, Ink-bottle effect and adjustment of modules can induce small errors.

Gas adsorption method use molecules to derive properties of soil pore; it requires heating soil sample to promote evaporation (Zachara *et al*. 2016). Analysis of sample was reported to be from soil sample of about 1 to 5 mm in diameter and pore size than can be investigated can be between 1 to 200 nm. The instruments for analysis are easily available, however, a common standard of pore are macro pores; those pores with diameter of 50 nm, and mesopores ranges between 5 to 50 nm, hence, micropores are 2 nm. The methodology requires heating samples and procedure takes a few hours to days to complete.

Imaging techniques are direct methods that can be used to visualize geometry of soil pore space, pores can be visualized in 2D and 3D of soil pore networks. Example of imaging technique are X-ray computed tomography, Gamma ray tomography, Neutron tomography and Nuclear magnetic resonance imaging. Rabot *et al*. (2018) summarized the ranges of samples sizes that can be determined, the authors reported that analysed sample range between cm^3 to dm^3 and pore size that can be viewed can be a few µm to hundred µm, also, the analysis takes few hours to complete, the equipment's are high in cost and the limitation of visualization is sensitive to the segmentation step and image resolution.

2.4 MICRO-FOCUS X- RAY COMPUTED TOMOGRAPHY

X-ray Microtomography (X-ray µCT) has become popular in recent decades, it has been widely applied in wide range of fields. Such include; Agriculture, medicine, civil engineering, biology and structural engineering. Tseng *et al*. (2018) evaluated soil physical and structural soil properties; Wang *et al*. (2018) characterized clay specimen before and after freeze-thaw and physical property; Grayling *et al*. (2018) traced particle movement in soil; Katuwal *et al*. (2015) also evaluated linking air and water transport intact soils to macropores. Tracy *et al.* (2015) studied the impact of soil compaction on root system architecture. Huining *et al*. (2018) found out that X-ray µCT is an effective means of measuring the moisture distribution in the internal structure of asphalt mixture.

Different authors employ and optimize different methods of using X-ray µCT and there is lack of unity in methods and terminologies. Glaying *et al*. (2018) used image processing software ImageJ 1.46r plugin for pore analysis while Carducci *et al.* (2017) used semi variance 3D plugin of the NIH ImageJ. New X-ray µCT are being produced and they come with their Algorithm and Plugins for analysis. For example, Wang *et al.* (2018) used Y. CT precision S-type X-ray µCT and Pöhlitz *et al.* (2018) used X-ray scanner (X-Tek X CT 225, Nikon metrology). Tsang *et al* (2018) used high resolution X-ray µCT and NRcon software from Embrapa Industrialization. However, they produce precise data even when they differ. In this study, Nikon XTH 225L micro-focus CT X-ray unit (Nikon Metrology, Leuven, Belgium), located at the MIXRAD laboratory at the South African Nuclear Energy Corporation, Pelindaba was used.

CHAPTER THREE

3.0 MATERIAL AND METHODS

3.1 Experimental Sites

This study was conducted in Limpopo province, South Africa, at Vhembe district under Thulamela and Collins Chabane local municipality. Soil samples were collected from four locations namely: Tshamutoro, Mukula, Ha-Davhana and University of Venda. Four soil forms were selected for the study namely: Glenrosa, Hutton, Shortlands and Dundee (Soil Classification Working Group 1991). A map showing the locations of the study area is presented in figure 1. Detailed description of soils can be acquired at Land Type Survey Staff. (2003) and land scape of the selected area of study is presented in figure 2. The equivalent soil types according to the IUSS Working Group WRB (2015) are given in brackets in the descriptions provided in the following section:

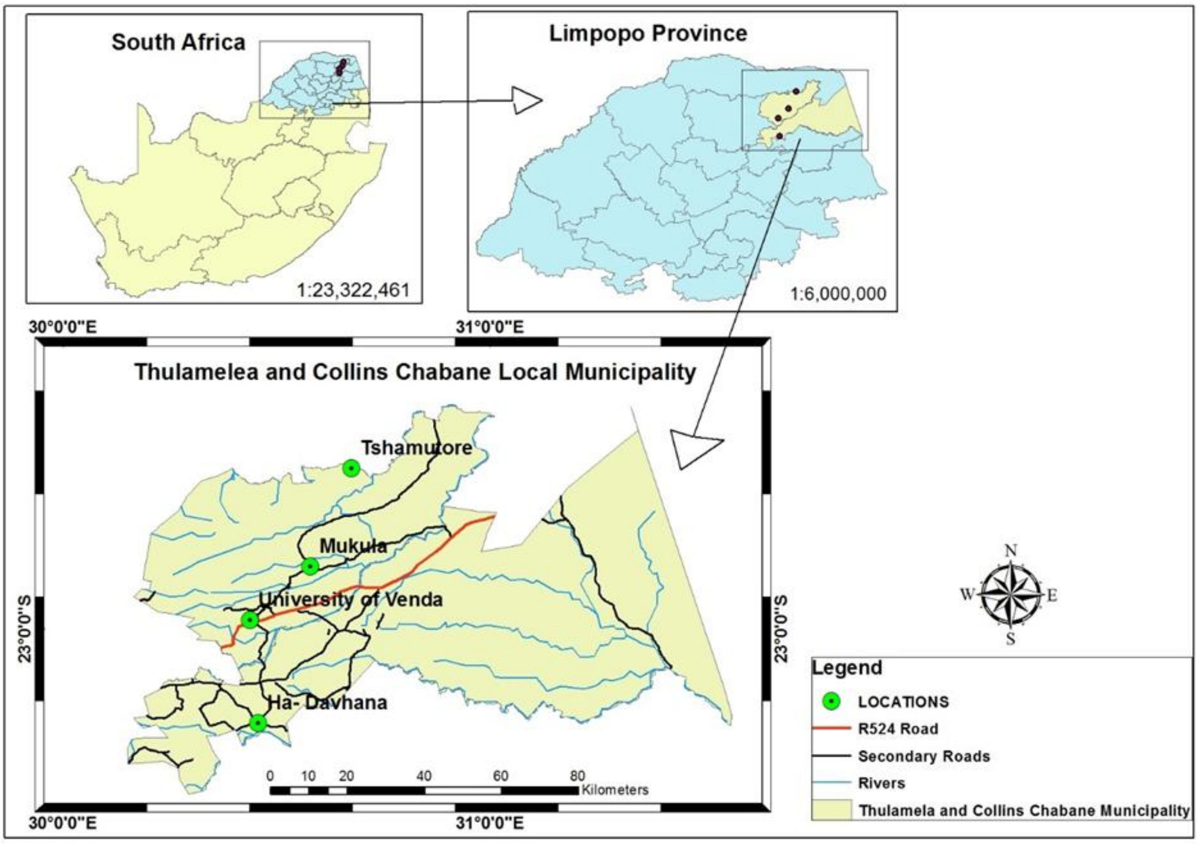


Figure 1: A map of the study locations.

3.1.1 GLENROSA (LEPTISOLS)

The Leptisols was collected at Ha-Davhana Village. The area is at latitude 23° 13' 09" S and longitude 30° 27' 25" E located at Collins Chabane local municipality in Vhembe west Region. The area is situated at 540 m altitude with a slope of 2%, vegetation/ land use is Grassveld. The terrain unit is upper mid slope and average annual rainfall is about 822 mm (range: 155-1209 mm). Weathering of underlying material is weak physical weathering and underlying materials consist of normal weathering. The soil is characterized by an Orthic A horizon overlying Lithocutanic B Horizon. Nonetheless, the soil consists of very shallow profile depth and contain large amount of gravel and underlying materials are genesis solid rock.

3.1.2 SHORTLANDS (LUVISOLS)

The Luvisols was collected at Mukula Village under Thulamela Municipality, which falls at latitude 0f 22° 51' 13" S and longitude of 30° 34' 44" E. The area is situated at 600 m altitude with a slope of 3%, terrain unit is Crest while annual rain fall average about 615 mm with a range of 99.6-773 mm. Shortlands soil form consist of Orthic A horizon overlying the Red Structured B horizon. Luvisols are fertile and widely used for Agriculture. They are also characterized by translocations of clay sized mineral particles from the A to the B horizon accompanied by normal weathering. Underlying materials is basic extrusive rocks and geological formation is Sibasa formation, Soutpansberg Group.

3.1.3 HUTTON (FERRALSOLS)

The Ferralsols soil was collected at the university of Venda experimental farm, which lies at the latitude of 22° 97' 61" S and Longitude of 30° 44' 65" E located at about 2 km away from the local town Thohoyandou, the area falls under Thulamela Municipality located at altitude of 596 m. Sampling location is a university experimental farm with a gentle slope of 8%, annual rainfall is about 780 mm (range: 218-1239 mm). The Hutton soil form consist of an Orthic A horizon overlying Red Apedal B horizon (Mzezewa and Van Rensburg, 2011). The soils are red and yellow in colour due metal oxide such as iron and Aluminum which dominate the soils. Underlying materials is Gneisis.

3.1.4 DUNDEE (FLUVISOLS)

This soil was collected at Tshamutoro village which falls at a latitude of 22° 37' 30" S and a longitude of 30° 40' 32" E under Thulamela municipality. The area is located at 884 m altitude with 2 % slope and slope shape is straight, also, land use is Bushland. Dundee soil Form has an Orthic A horizon overlying a stratified alluvium. They can be Non-Red stratified alluvium, and Red stratified alluvium. Hence, they are used most often in crop production. Underlying materials is sandstones (siliceous) susceptible to slight wind erosion and parent material Solum is Origin single, solid rock (Loock *et al*. 2003).

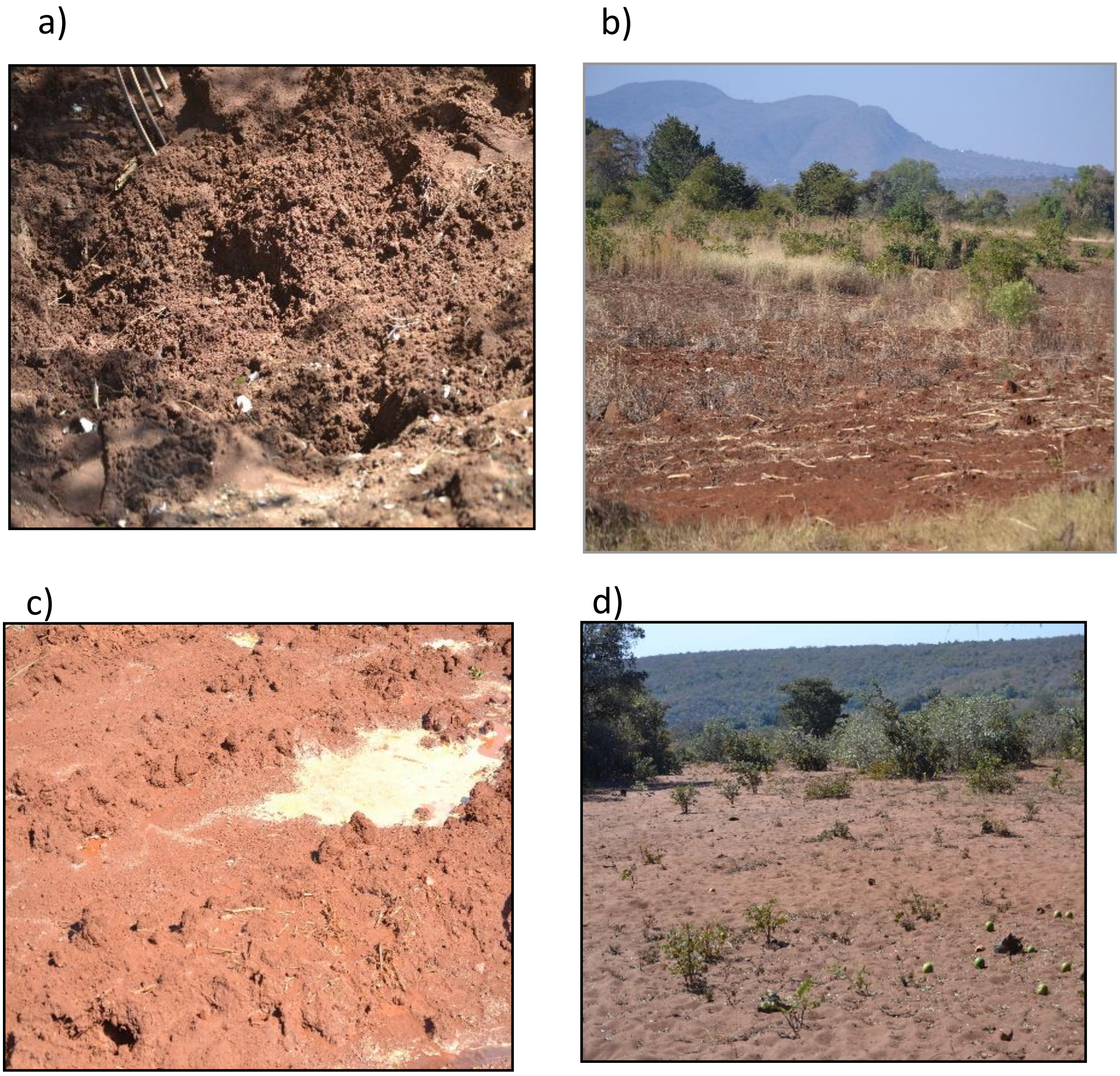


Figure 2: Selected soils for the study (a), Glenrosa (b), Shortlands (c), Hutton and (d) Dundee in Limpopo South Africa.

3.2 SOIL SAMPLING

The selected area was irrigated and allowed to drain for 24 hours before sampling. A rigid polyvinyl chloride (PVC) pipe with inner diameter of 50 mm, wall thickness of 2 mm and length of 300 mm was used. In addition, the edges of the PVC pipes were sharpened to assist penetration. In order to protect the samples from mechanical disturbances, a PVC pipe stopper suitable for 50 mm pipes was used after sampling to protect the bottom part of the samples to protect the sample from sliding down the pipe in movement; furthermore, the cores were placed in a cooler bag wrapped with sponge to protect the sample to avoid internal structural damages during transportation from field to laboratory.

Each site consisted of two adjacent sampling locations namely, visibly crusted (VC) and not visibly crusted (NCV) four samples in each adjacent sampling location was collected. Samples were oven dried at 40° C for approximately 30 days until mass becomes constant, the selected methods were chosen over traditional 105° C oven temperature to maintain integrity of the cylinder and to reduce changes in the sample volume since some soils were clay soils. The samples were transported from University of Venda to Micro-focus X-ray Radiography and Tomography laboratory at Necsa (MIXRAD) for Micro-focus X-ray computed tomography (MXCT) analysis (Hu *et al*., 2018; Yang *et al*. 2017; Borges *et al*. 2019; Carducci et al. 2014b; Jefferries *et al*. 2014).

3.3 EXPERIMENTAL PROCEDURE

In this study, a representative sample from each soil form was selected from each soil form, an area that is VC and NCV was scanned and analysed, Due to the height of the PVC pipes, the micro-focus CT X-ray unit could not scan the whole sample and therefore each sample was divided into top part, that is (0-10 cm) and bottom (10-25cm). As a result, a total number of 4 samples were scanned per treatment. The samples were scanned using a Nikon XTH 225L micro-focus CTX-ray unit (Nikon Metrology, Leuven, Belgium), located at the MIXRAD laboratory at the South African Nuclear Energy Corporation (Necsa), Pelindaba. Scanning parameter was set to 100 kV and 180 µA to optimise penetration of X-rays through the soil aggregates with a 0.1 mm copper filter (Malobane et al. 2019).

The scanning pixel resolution was set to 31 µm in order to visualize the soil microstructure. An aluminium filter was used to approximate a homogeneous X-ray beam spectrum of high X-ray photons that contributes to noise. The X-ray machine acquires a shading correction image that is used to calibrate the background of the acquired radiographs. The samples were securely mounted in a polystyrene mould to avoid any movement during each scan. The mounted specimens were then placed on to a rotating sample manipulator, which facilitated scanning at 360°. In this experiment, up to 100 slices were acquired in one rotation with one thousand projection images obtained in the 360° at 2 seconds exposure time for each projection, each scan took 30 minutes to obtain tomographs (Huining *et al*. 2016). Size of Tomographs was 16 bit TIFF and each image stack/tomographs had a size of at least 15 GB. Tomographs were imported into Nikon CTPro software® (Nikon Metrology, Leuven, Belgium) for reconstruction. Image stacks were cropped to remove slices at the top and bottom of the core and further analysed using VGStudio Max V3.2 ® (volume Graphics GmbH, Heidelberg, Germany). A region of interest (ROI) of 7575 mm^2 volume was selected in the middle of soil sample to exclude voids near core walls and minimize beam hardening interference. A value of 97 in a range of 0 to 255 was selected as the threshold value for analysis of images (Hu *et al*. 2018). For 3D structure analysis, soil pores were classified according to the size and shape distribution. Volume intervals of pores were selected based on the difference pore sizes for water movement and retention (Galdos *et al*. 2018). Classification of pore system based on diameter adopted in this study was proposed by Brewer (1964), which indicate that; pores with equivalent cylindrical diameter of > 2000 µm are considered medium to coarse macropores, those between 1000 and 2000 µm fine macropores, between 75 and 1000 µm very fine macropores, between 30 and 75 µm mesopores and < 30 µm micropores. Sphericity (S) from 3D data defects was used to classify pore into three pore shape classes: Regular pores (S≥ 0.5), Irregular pores (0.2 < S < 0.5) and Elongated pores (S ≤ 0.2) (Zhou et al., 2012; 2017). 3D porosity was calculated based on the relationship between total volumes of voids divided by the total number of volume (Pires et al. 2017)

3.5 DATA ANALYSIS

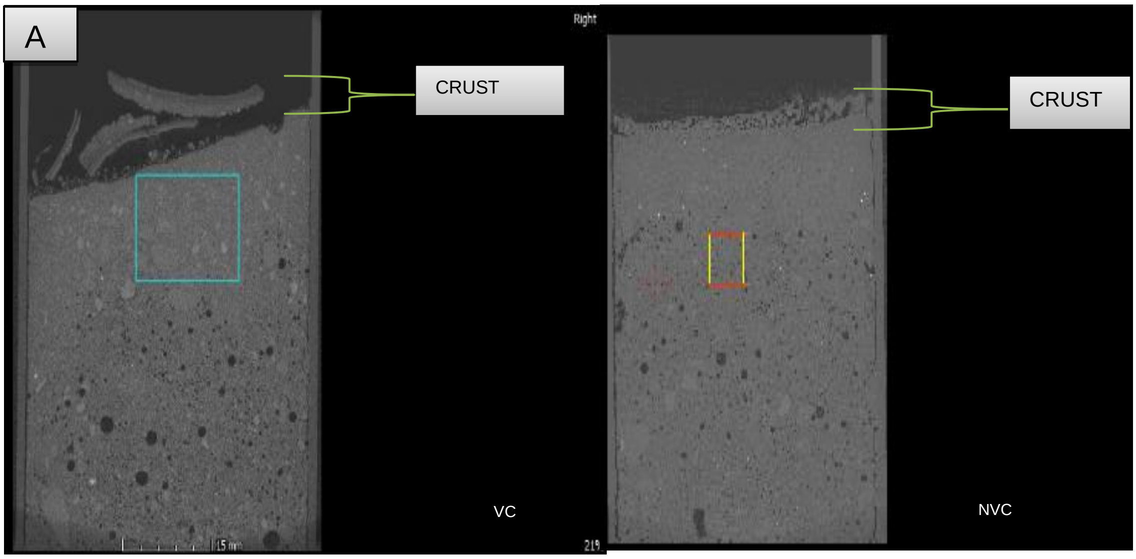
The results were expressed as image data. Re-construction of three-dimensional volume data set of pore shapes, pore size and porosity among the soils was performed using CTPro software® (Nikon Metrology, Leuven, Belgium). Combined analyses and differences of data set were further analyzed using VGStudio Max 3.0® (Volume Graphics GmbH, Heidelberg, Germany).

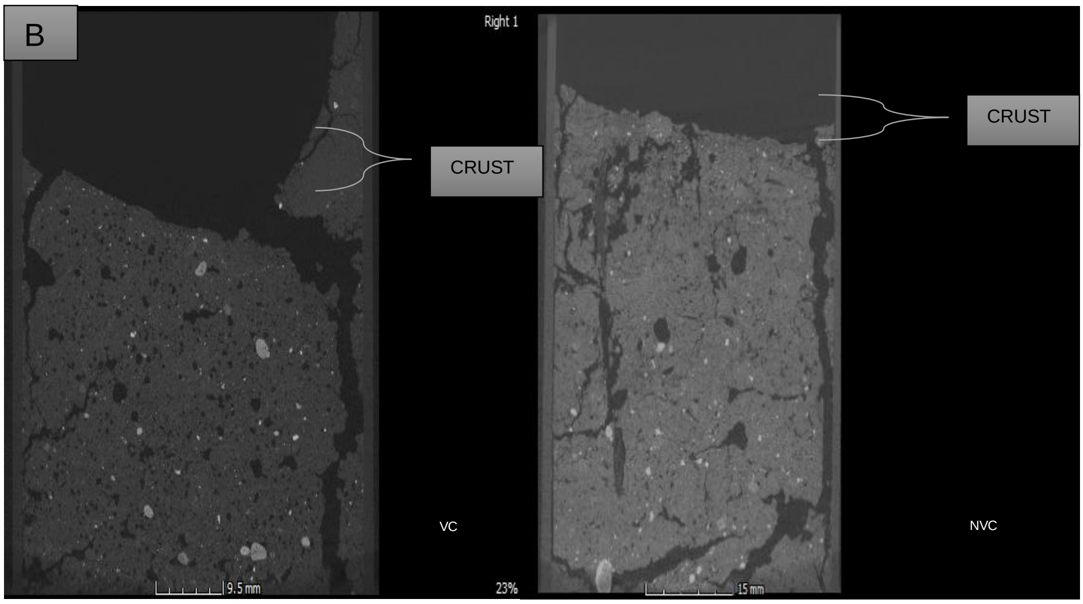
CHAPTER FOUR

4.0 RESULTS

4.1 Visualization of crust in 2D

Visualization of soil micro pores in the vertical/ longitudinal column of selected samples in each soil forms are shown in Figure 3. It is evident that, soils in VC contain less dense particles thus forming more crust compared to NVC soils. However, Glenrosa soil form shows thick visible crust compared to the other soils, while Dundee soils are the least because of their sandy characteristics. It is evident in the longitudinal view that pore distribution is complex however, Shortlands and Hutton soils had large voids compared to Dundee and Glenrosa soils due to their swelling and expanding clay characteristics.




B
Right 1
CRUST
CRUST
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NVC
9.5 mm
15 mm
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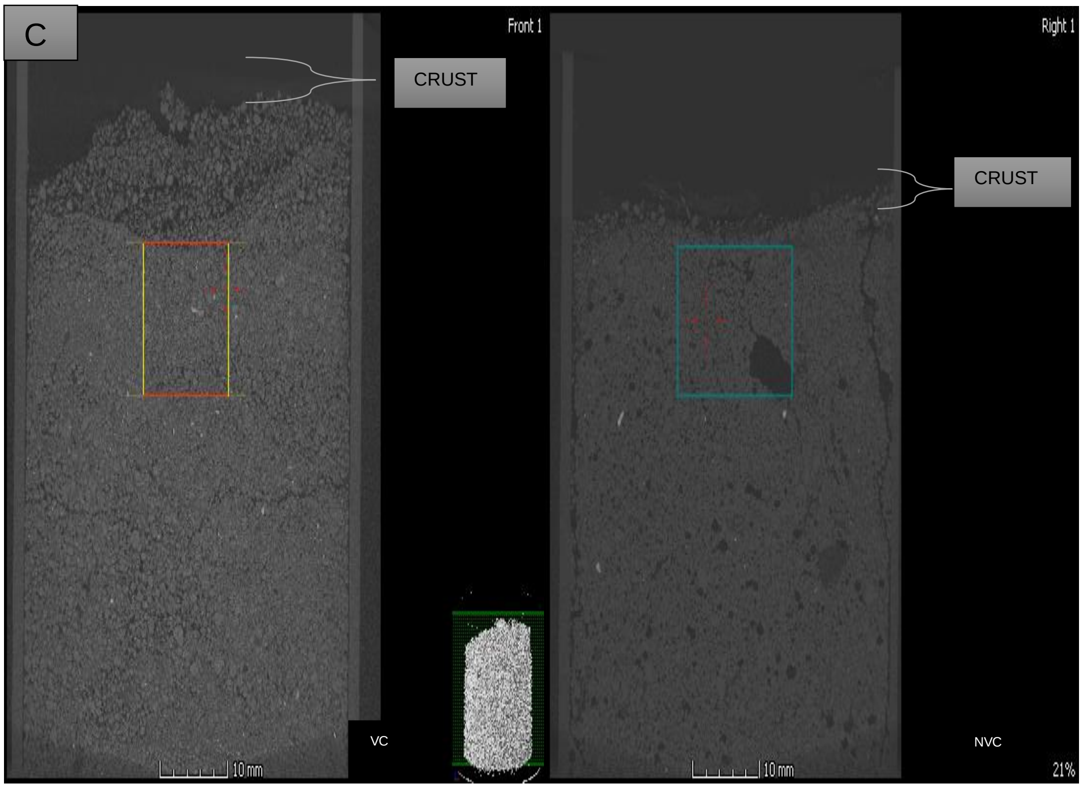
C
Front 1
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CRUST
CRUST
VC
NVC
10 mm
10 mm
21%

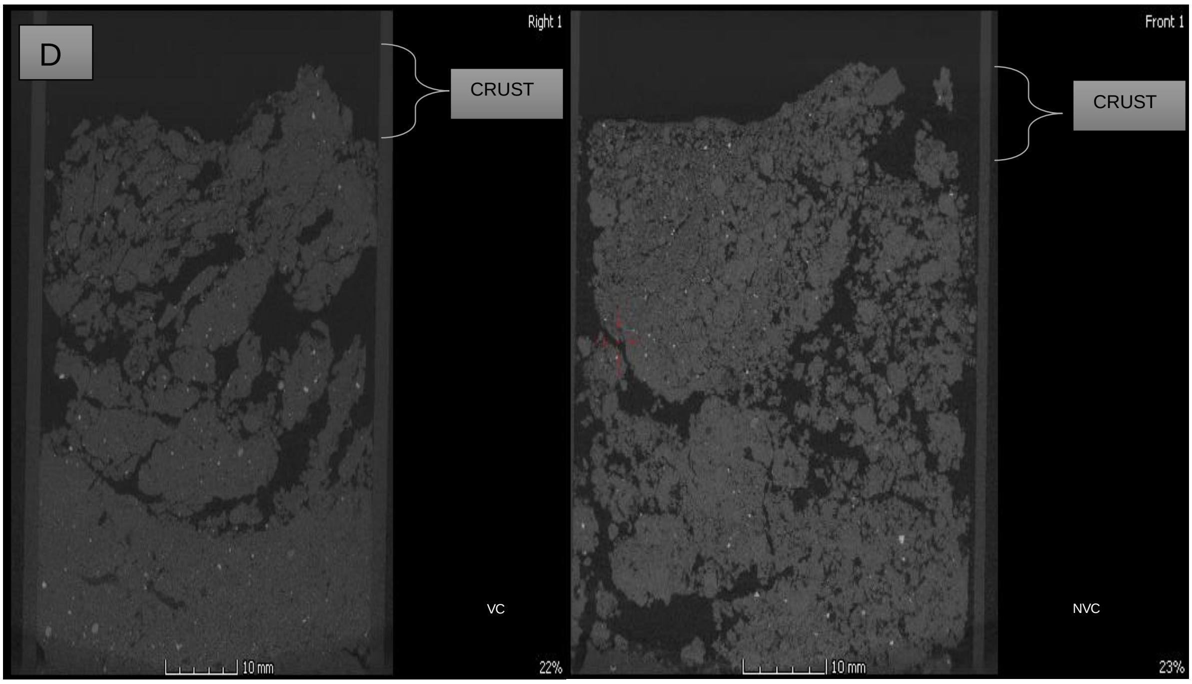
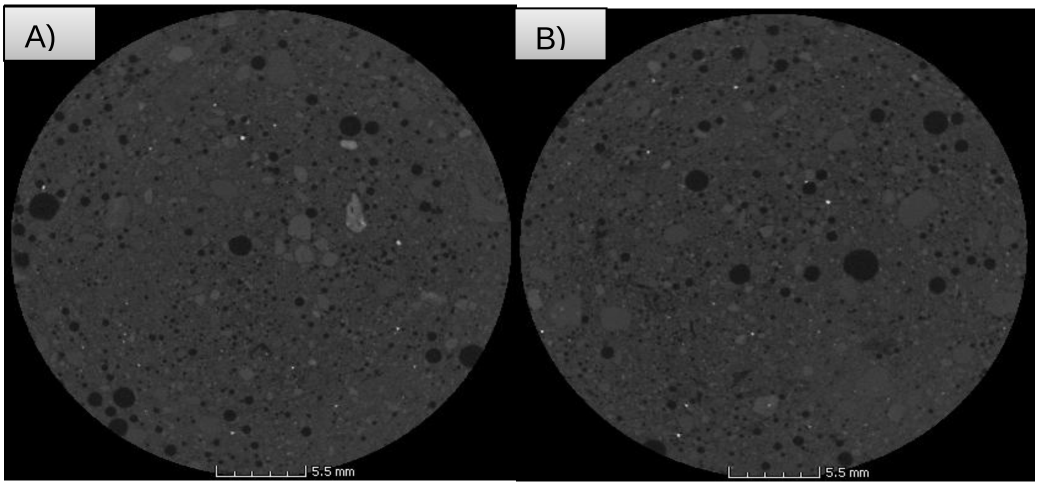


Figure 3. 2D Greyscale Comparison of crust development in Glenrosa (A) , Shortlands (B), Dundee (C) and Hutton (D) soils in VC and NVC (black colour represents pore spaces , grey colour is solid part and white colour is iron or aluminium oxides).

Figure 3 shows a horizontal view of soils produced from X-ray CT scan. The images were developed before 3D images were constructed and Region of interest (ROI) was selected. Crust development are not visible in horizontal view in both VC and NVC soils.



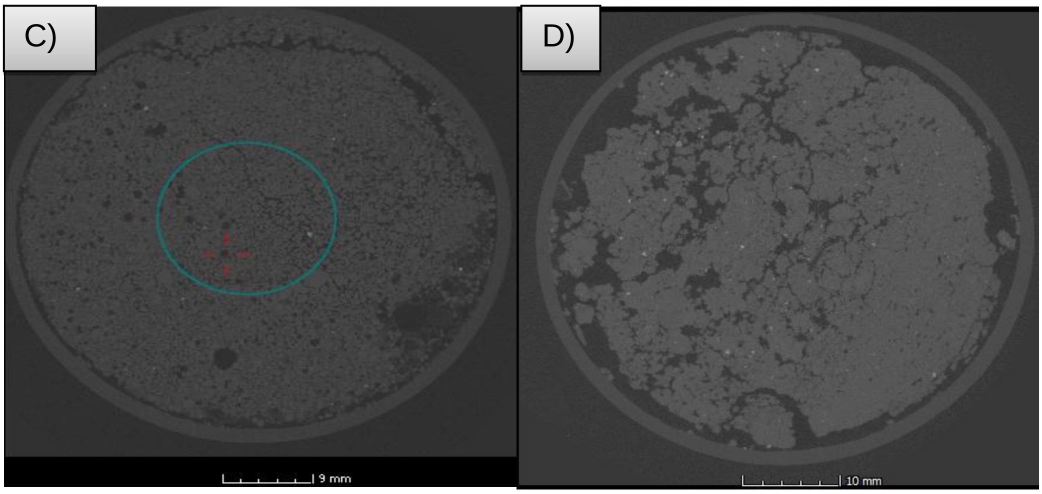


Figure 4a: 2D Greyscale *Horizontal view of NVC with a volume grid coordinates: A) Glenrosa (32.30392 mm), B) Shortlands (22.49766 mm), C) Dundee (38.61024 mm), D) Hutton (30.56973 mm), black colour represents pore spaces, grey colour is solid part and white colour is iron or aluminium oxides.*

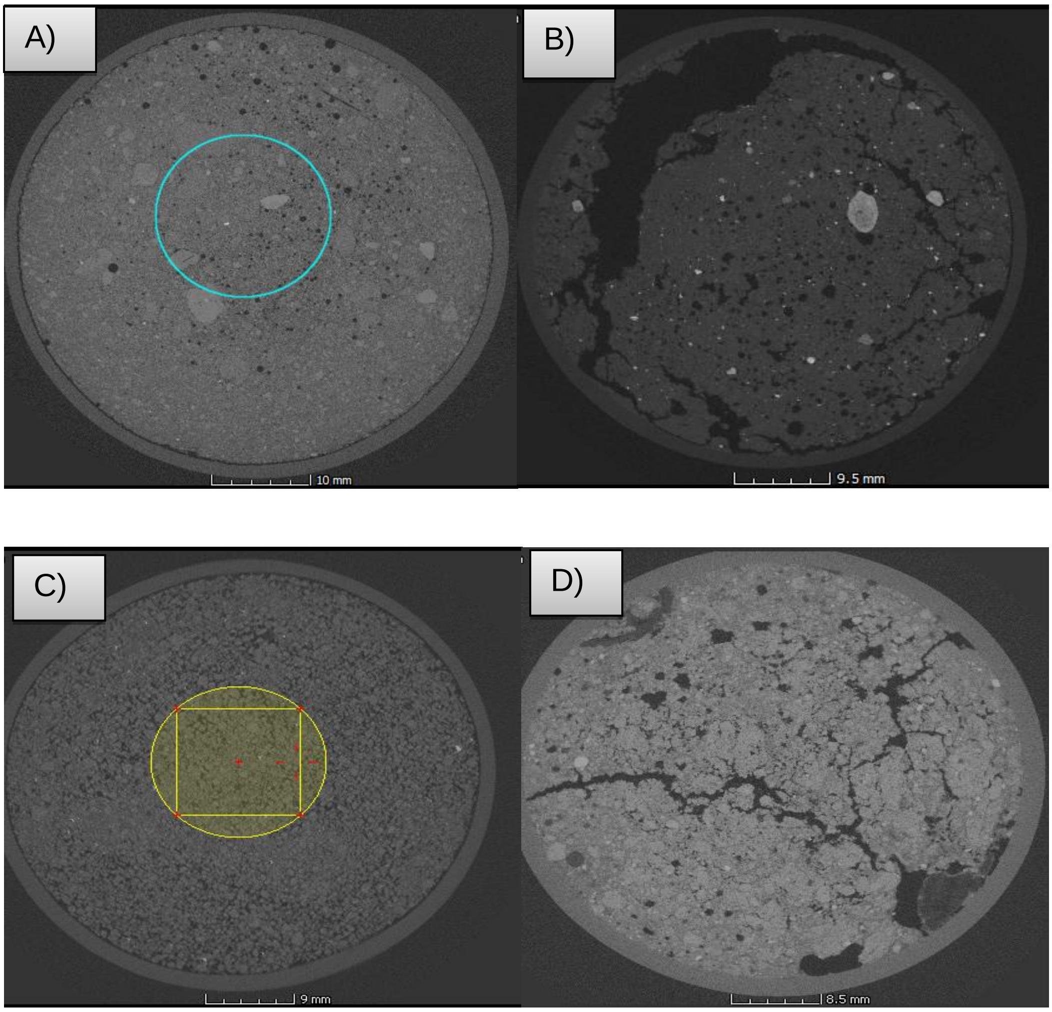


Figure 4b: 2D Greyscale Horizontal view of VC with a volume grid coordinates: A) Glenrosa (32.30395 mm), B) Shortlands (29.02465 mm), C) Dundee (31.51567 mm), D) Hutton (31.04270 mm), black colour represents pore spaces, grey colour is solid part and white colour is iron or aluminium oxides.

Selection of RIO was conducted using VGStudio max 3.2®, see Figure 5. The RIO was selected at an area that is less disturbed to mimic natural soil body pore description. Figure 5 (a) shows a 2D scale with selected RIO in the middle, Figure 5 (b) shows an analysed pore image in 3D without removal of other pores surrounding, while Figure 4(c) shows a selected 3D images of the entire sample.

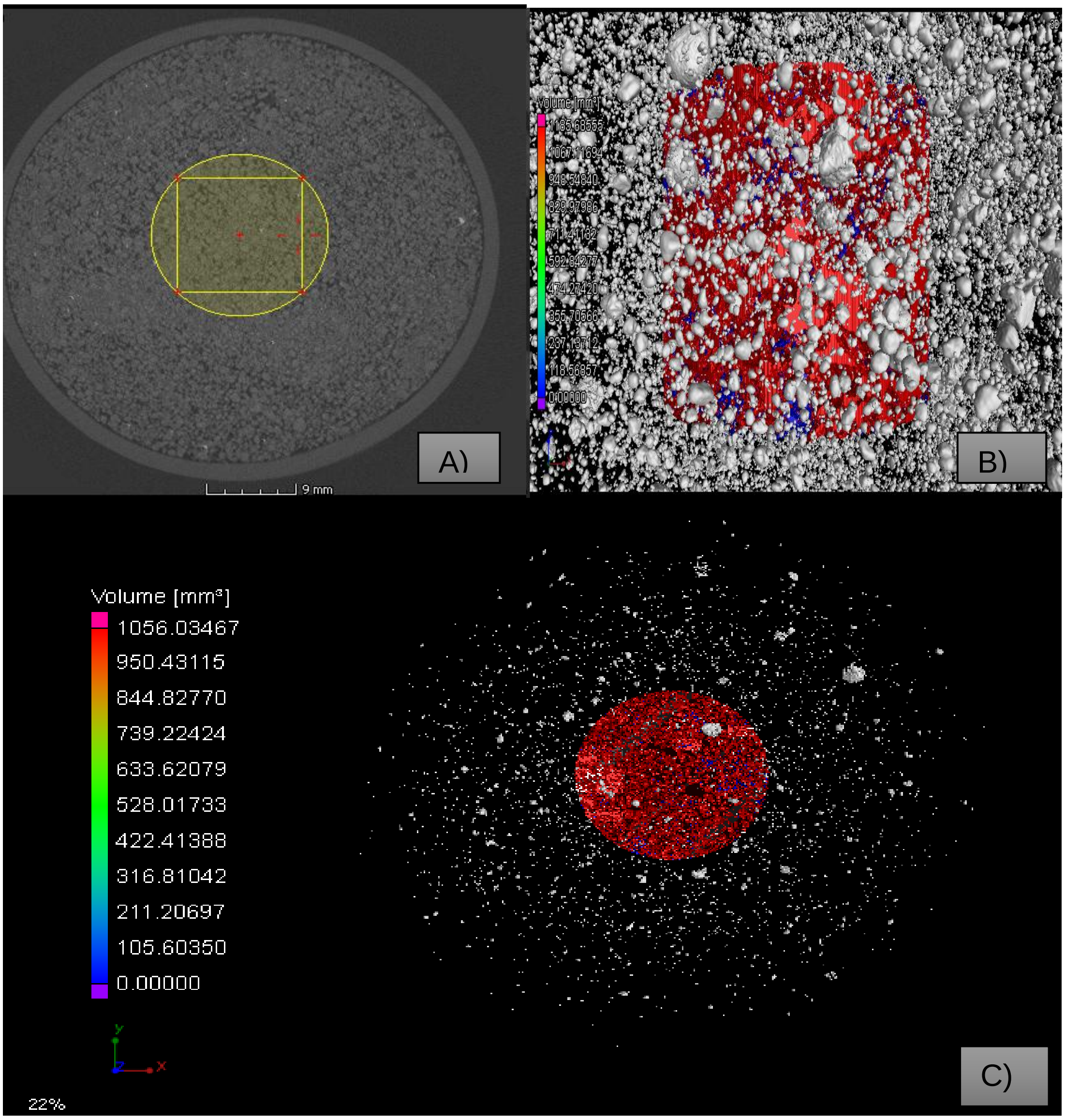


Figure 5: Virtual example of selected RIO using CT in 3D and 2D.

Micro-porosity aggregate structure.

Micro porosity of soil differs with soil type (Table 1 and 2). The micro tomography showed that the pores increased with an increase in porosity. For example, in Hutton soil form of visibly crusted (VC), number of pore decrease with increase in depth. However, in NVC soil, there is a slight difference with changes in number of pores. Glenrosa soils of VC consist of high porosity of 1.9715 in 0-10 cm depth and decrease to 0.2574 at 10-25 cm depth. Soil crust is shown in Figure 8-12 in 3D.

4.2 Morphometric characteristics of aggregate

Morphology of soils in VC and NCV in 3D is shown in figure 6-14. Detailed description is indicated in Table 1 and 2. The shape of aggregates is the characteristic of soil morphology aggregates. Interesting results from the analysis indicate that all soils studied was dominated by regular pore shape that amount to > 70%. Decrease in cracks and elongated pore with increase in depth was evident in visual observation of 3D images. Hutton soils indicate a higher connectivity between the pores in topsoil which is related to hydraulic and gaseous conductivity. In terms of porous connections and distribution of aggregates sizes, see Figure 6.

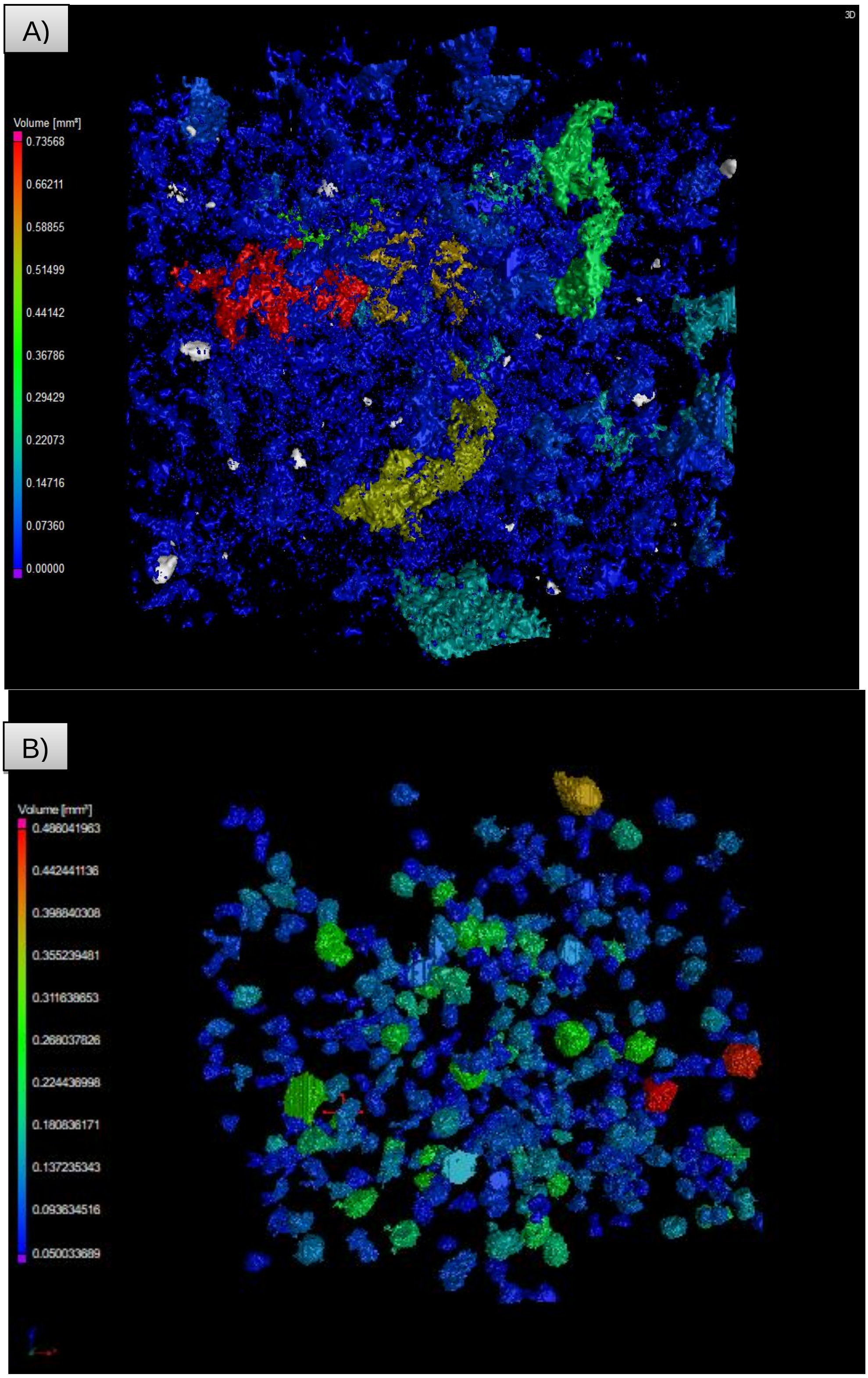


Figure 6. Soil micro aggregates visualisation in 3D of selected soils; A) Hutton, B) Shortlands soil form.

Soil form	Hutton (ferralsols)				Glenrosa (Leptsols)			
Parameters	V_C		N_{VC}					
Depth		0-10cm &	10-25cm			0-10cm &	10-25cm	
Total porosity ($mm^3\ mm^{-3}$)	38.4468	0.6960	5.5081	5.5093	1.9715	0.2574	2.3417	1.9686
Pore diameter (mm)	0.0540	0.04704	0.0621	0.0621	0.0467	0.03153	0.0590	0.06872
Number of pores	9365.3947	12910.3874	9944.3365	9944.3661	6700.9022	8512.3681	7918.9331	6266.2875
Mean Voxel size	222.9652	2.5942	34.6581	34.6581	13.864	1.0015	17.5770	21.7324
.								
PSD %								
<30µm	0	0	0	0	0	0	0	
30- 75µm	3.1720	7.03479	3.2348	3.2348	1.2138	2.075	3.0557	0.7201
75-1000µm	7.339	8.0673	0.5179	0.1096	0.0042	0.0000	5.2298	0.0081
>1000µm	0.6660	0.0268	0.3286	0.3286	0.0091	0.0000	0.0737	0.0286
Pore shape distribution %								
Regular pore	76.6547	70.8078	75.1089	75.089	78.0343	80.9991	75.5147	73.6748
Elongated pore	2.3382	4.3652	11.7230	11.7230	0.9654	0.0003	1.9770	3.1631
Irregular pore	0.0009	0.0013	0.0081	0.0082	0.0005	0	0.0012	0.0027

Table 1. General Properties of soil pore aggregates of two soils (Hutton and Glenrosa) in visibly crusted (VC) and not visibly crusted (NVC) Soils, Particle size Distribution (PSD), pore shape distribution (%) and two soil depth. Mean Standard Deviation from (0.001-0.9).

Soil form	Dundee (fluvisols)				Shortlands (Luvisols)			
Parameters	V_C		N_{VC}					
Depth		0-10cm	&	10-25cm		0-10cm	&	10-25cm
Total porosity (mm^3 mm^{-3})	18.8243	6.5924	32.0498	26.3020	31.3154	7.1073	26.7243	2.9714
Pore diameter (mm)	0.04380	0.0443	0.0621	0.0503	0.0549	0.0503	0.05879	0.0493
Number of pores	17883.0495	6649.5471	8885.5883	8401.1652	26290.9451	20164.6154	45664.5189	20402.7351
Mean Voxel size	248.5494	236.7996	181.4587	167.0994	65.7860	17.8868	34.5981	7.2678
PSD %								
<30µm	0	0	0	0	0	0	0	0
30- 75µm	3.1720	3.5428	3.4698	3.4019	3.4496	3.4079	3.5172	35041
75-100µm	7.339	4.4290	5.0072	3.8298	3.8538	3.7172	5.8994	0.0148
>100µm	0.6660	0.0145	0.0499	1.4999	1.6598	1.3545	0.0075	0.1182
Pore shape distribution %								
Regular pores	76.6547	78.60366	77.3676	76.7356	76.4496	75.5147	75.9705	77.6156
Elongated pores	2.3382	0.135	0.4079	0.6996	5.2118	1.9770	0.0800	18.3906
Irregular pores	0.0009	0.0006	5.0072	0.000	0.0013	0.0012	0.0000	0.0056

Table 2. General properties of soil pore aggregates of two soils (Dundee and Shortlands) in visibly crusted (VC) and not visibly crusted (NVC) Soils, Particle size Distribution, pore shape distribution and two soil depth. Mean Standard Deviation ranged (0.001).

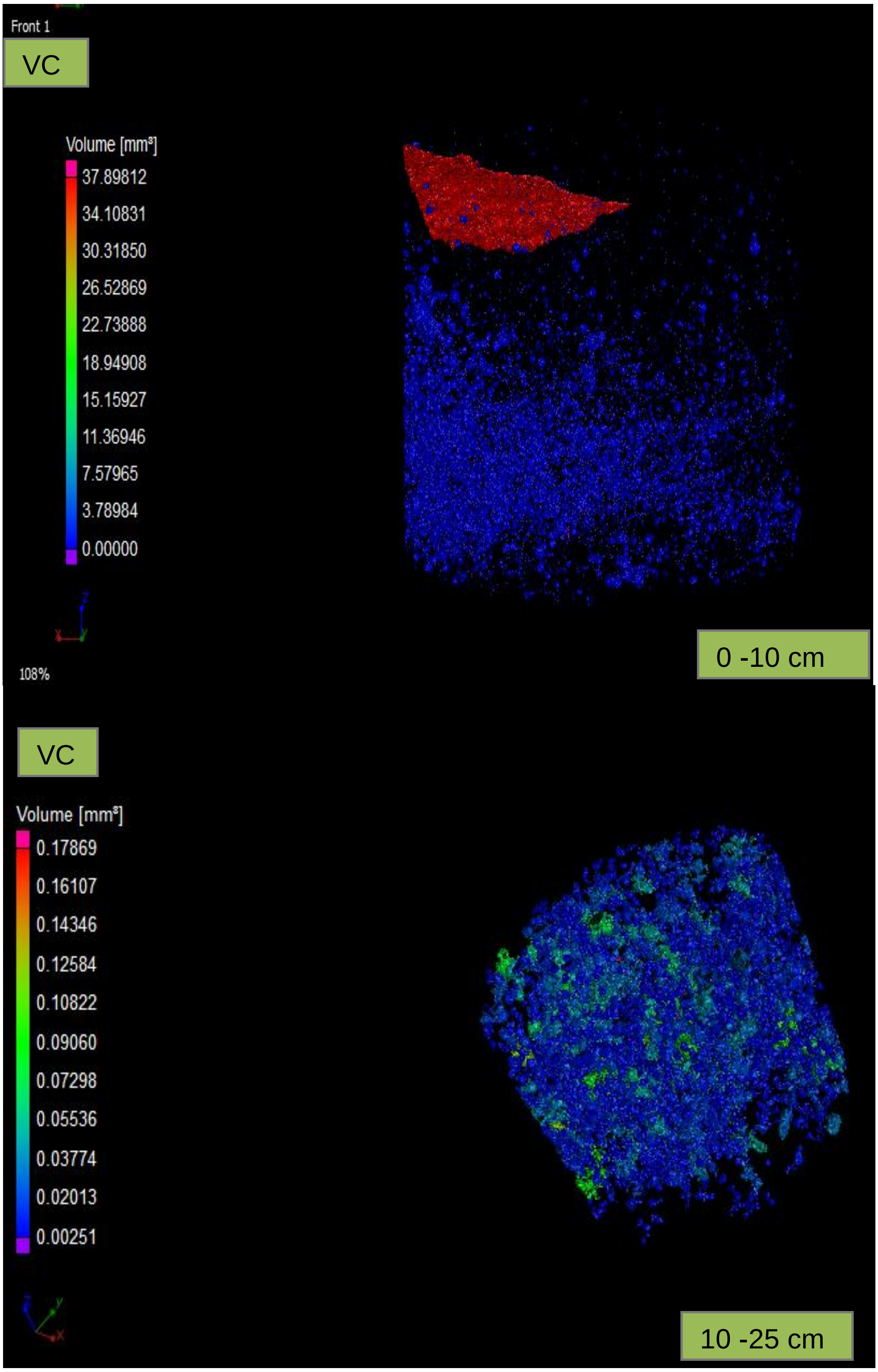


Figure 7. Representative of pore system obtained from X-ray computed tomography in Glenrosa soil form from Visibly crusted (VC) area in two adjacent depth (0-10 cm and 10- 25 cm).

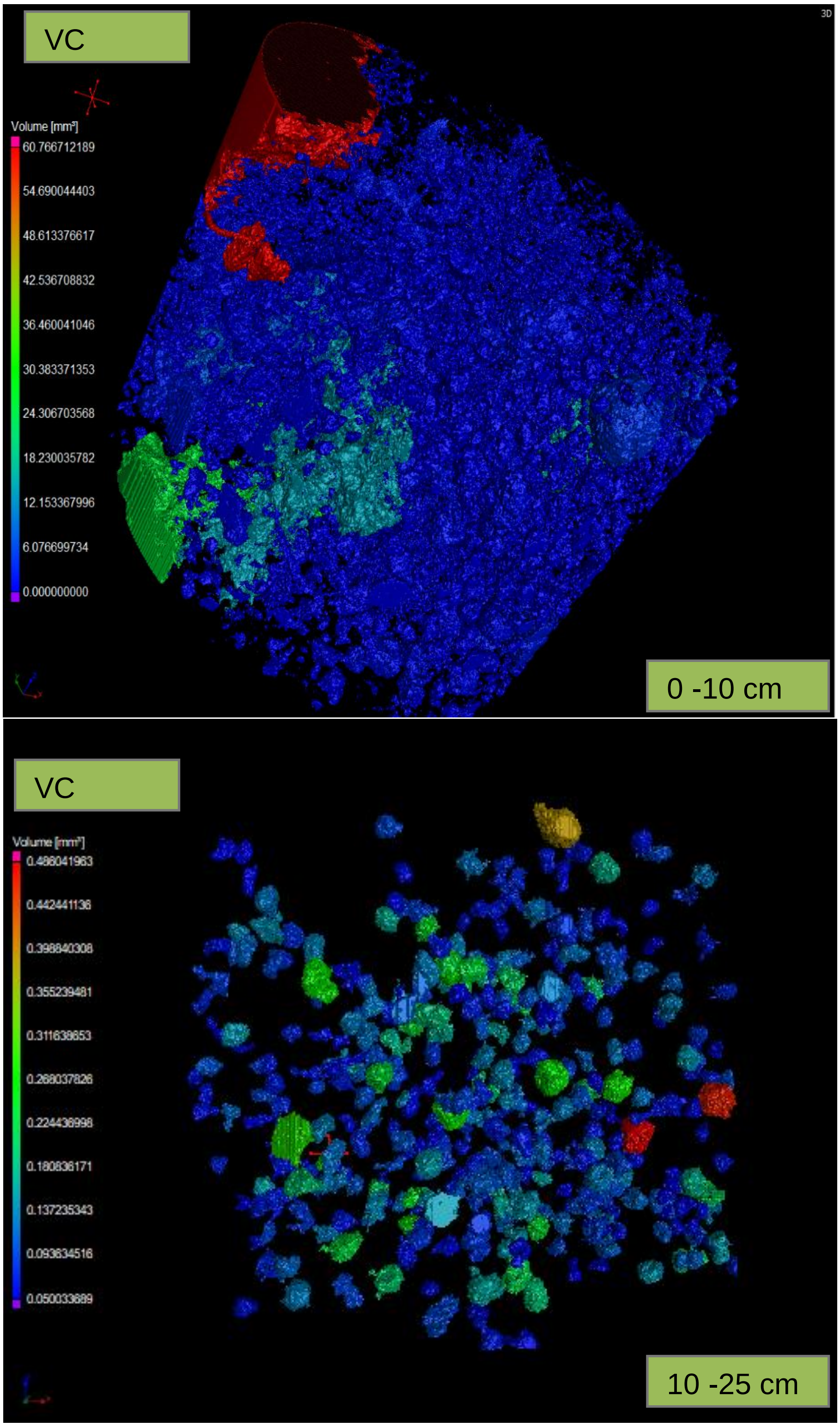


Figure 8. 3D Representative of pore system obtained from X-ray computed tomography in Shortlands soil form from visibly crusted (VC) area in two adjacent depth (0-10 cm and 10- 25 cm).

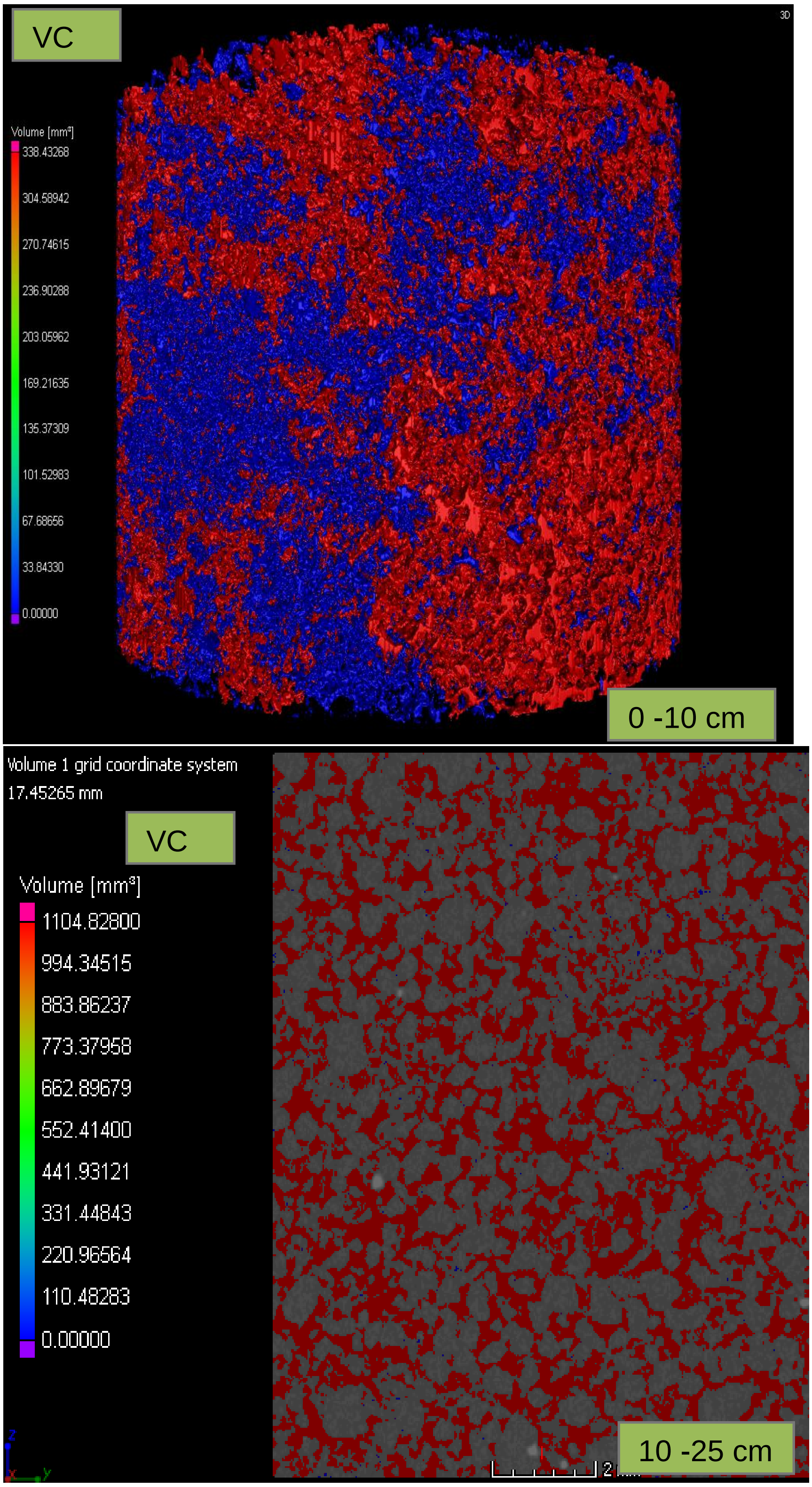
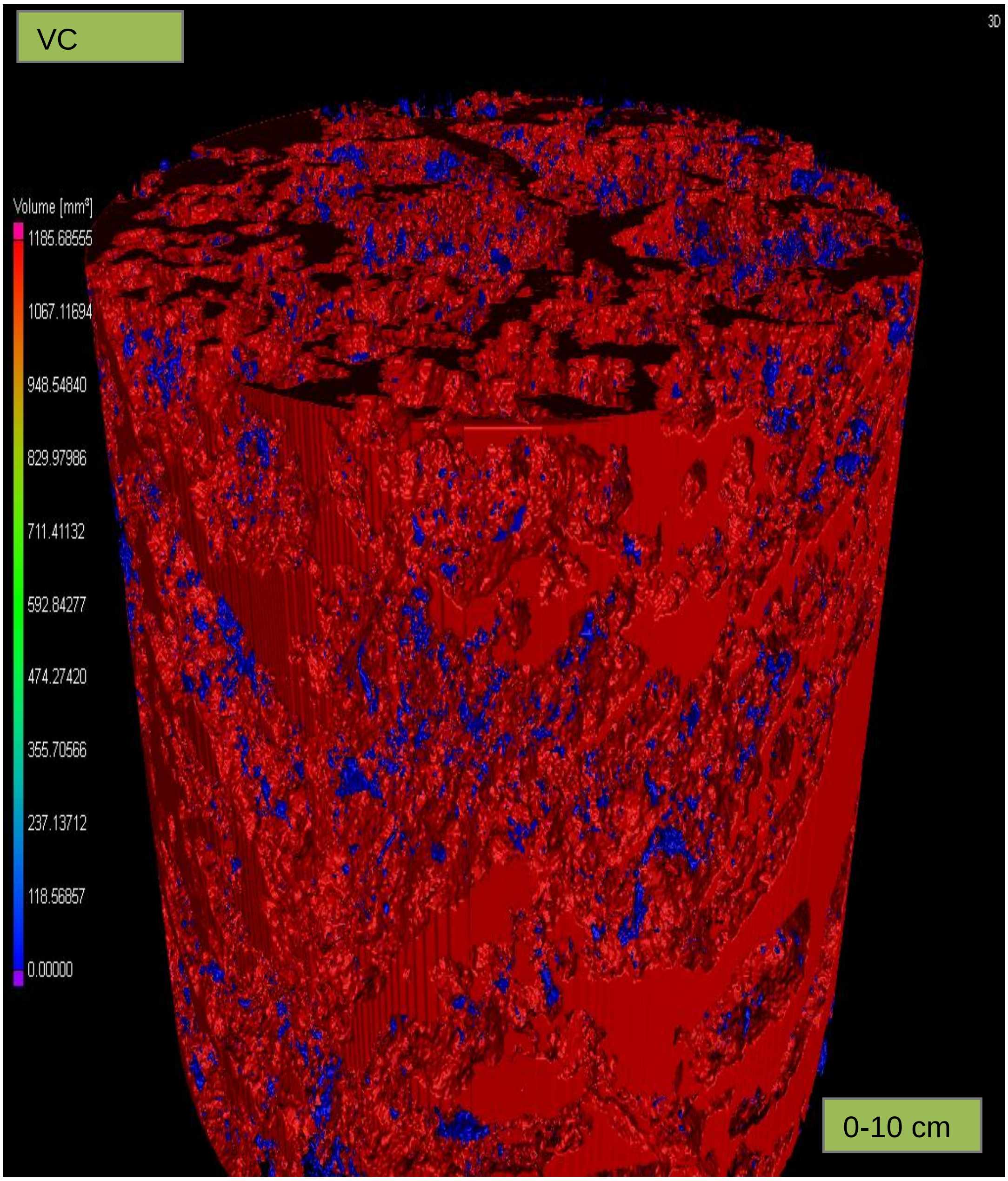


Figure 9. 3D Representative of pore system obtained from X-ray computed tomography in Dundee soil form from Visibly crusted (VC) area in two adjacent depth (0-10 cm and 10- 25 cm).


VC
3D
Volume [mm³]
1185.68555
1067.11694
948.54840
829.97986
711.41132
592.84277
474.27420
355.70566
237.13712
118.56857
0.00000
0-10 cm

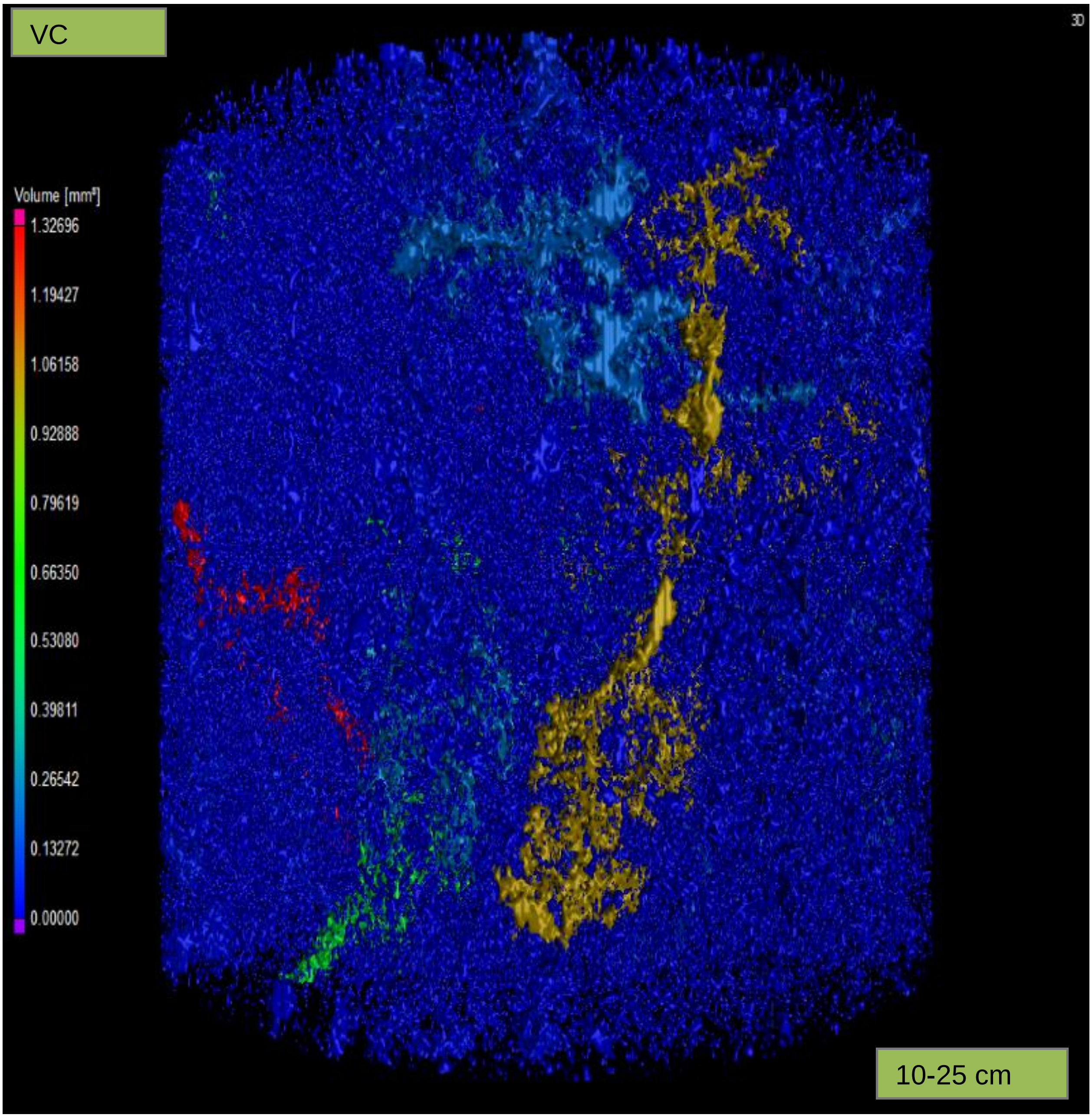


Figure 10.3D Representative of pore system obtained from X-ray computed tomography in Hutton soil form from Visibly crusted (VC) area in two adjacent depth (0-10 cm and 10- 25 cm).

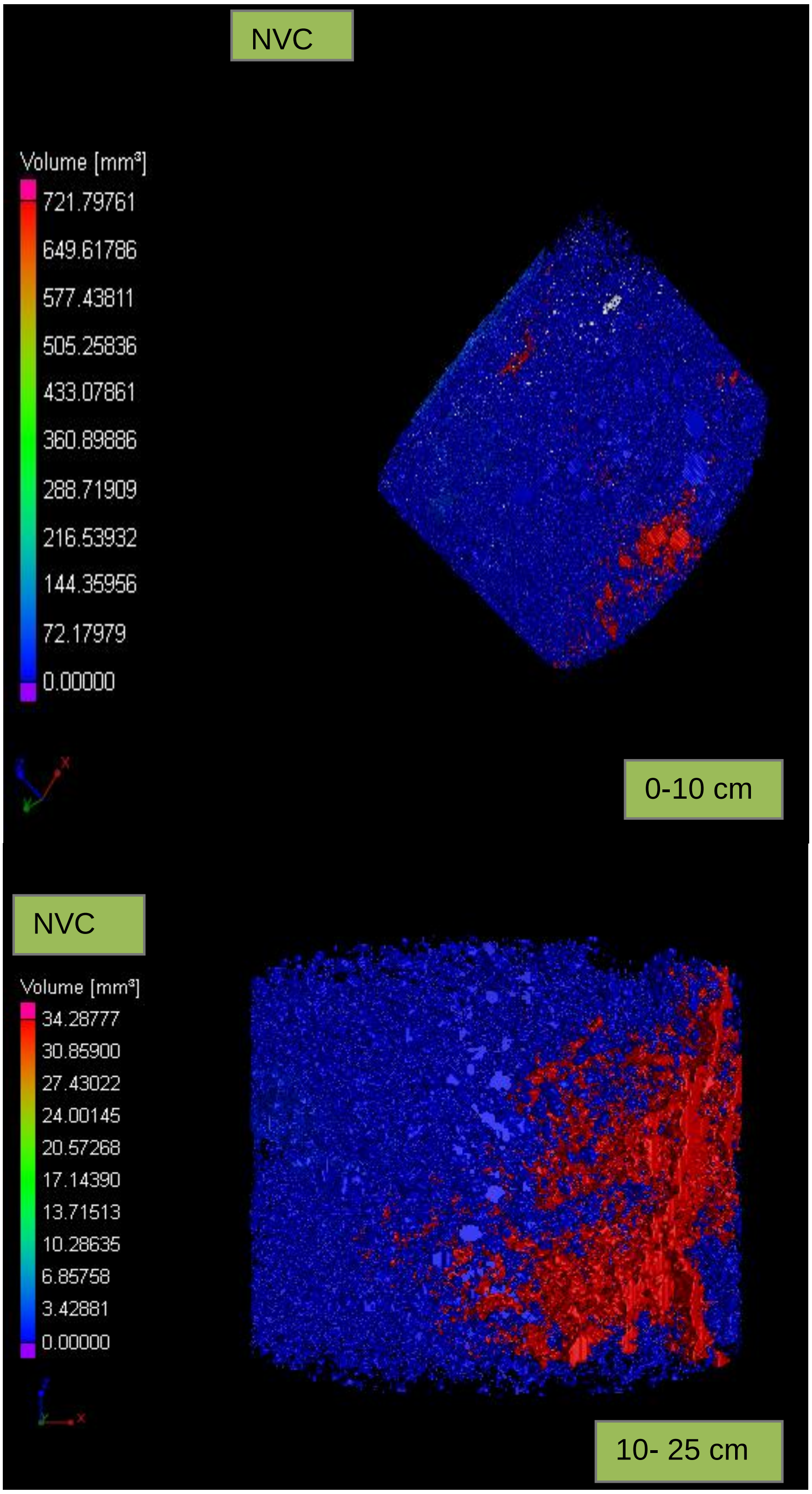


Figure 11. Representative of pore system obtained from X-ray computed tomography in Glenrosa soil form from NVC area in two adjacent depth (0-10 cm and 10- 25 cm).

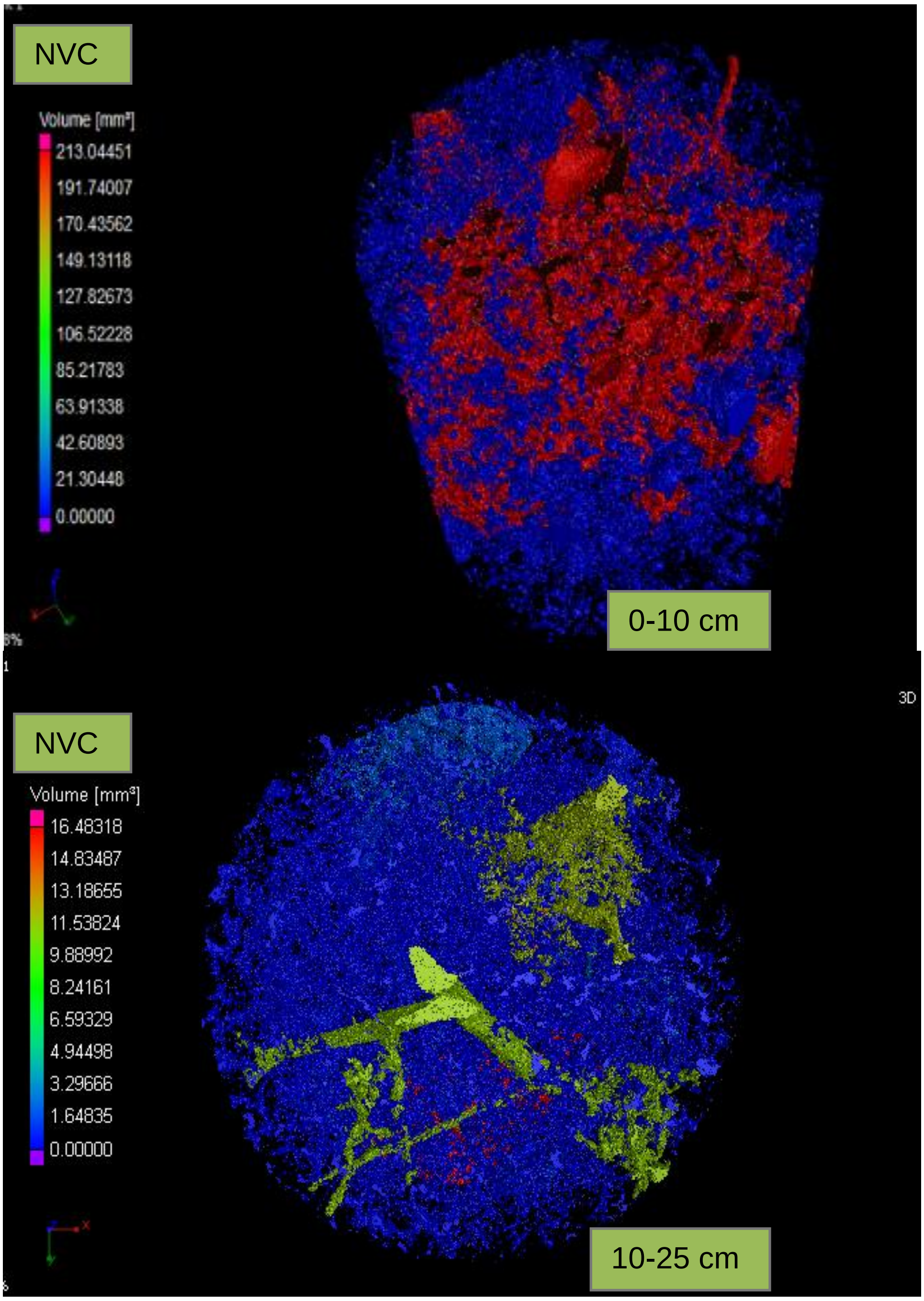


Figure 12: Representative of pore system obtained from X-ray computed tomography in Shortlands soil form from NVC area in two adjacent depth (0-10 cm and 10- 25 cm).

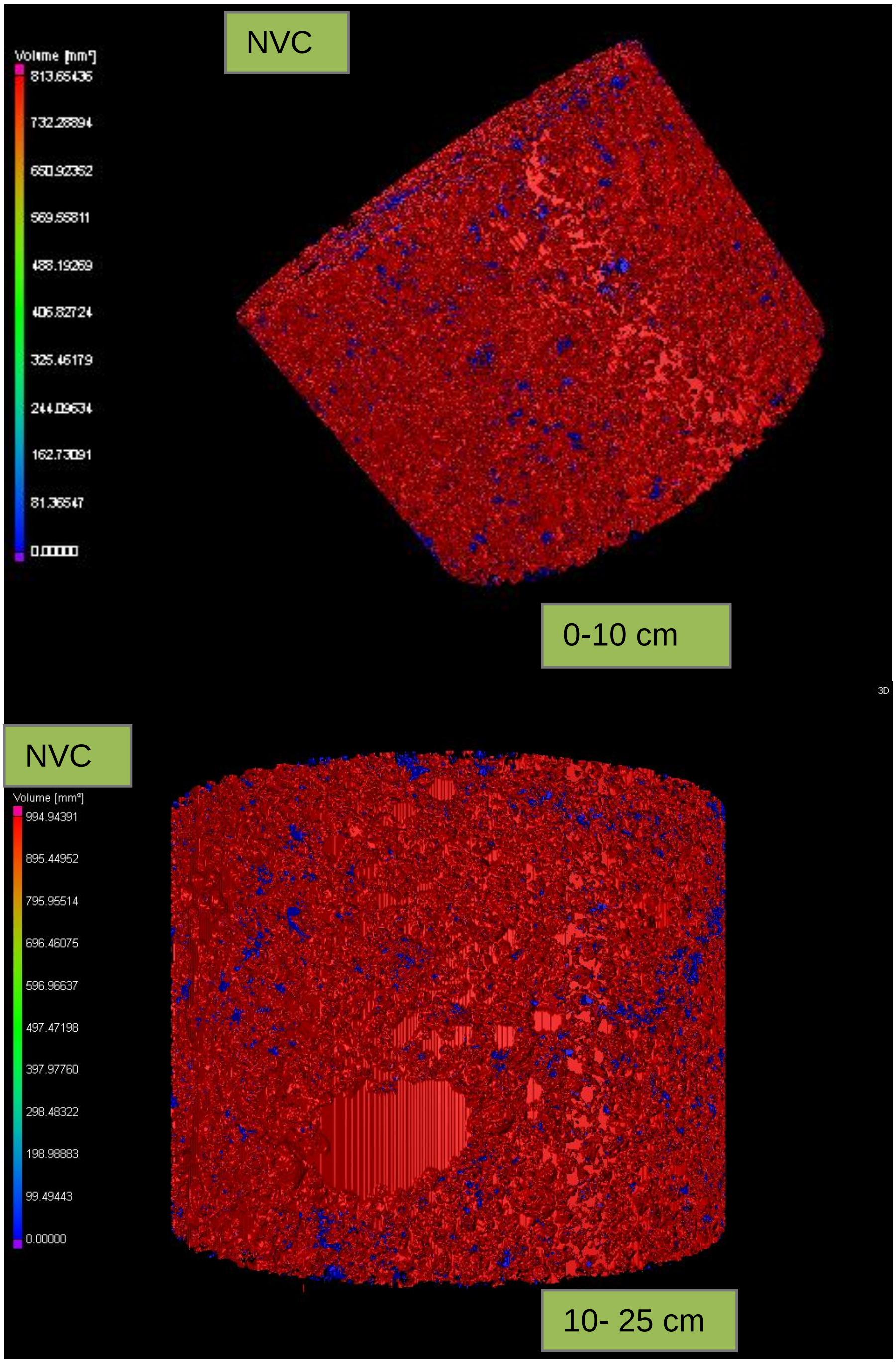


Figure 13. Representative of pore system obtained from X-ray computed tomography in Dundee soil form from NVC area in two adjacent depth (0-10 cm and 10- 25 cm).

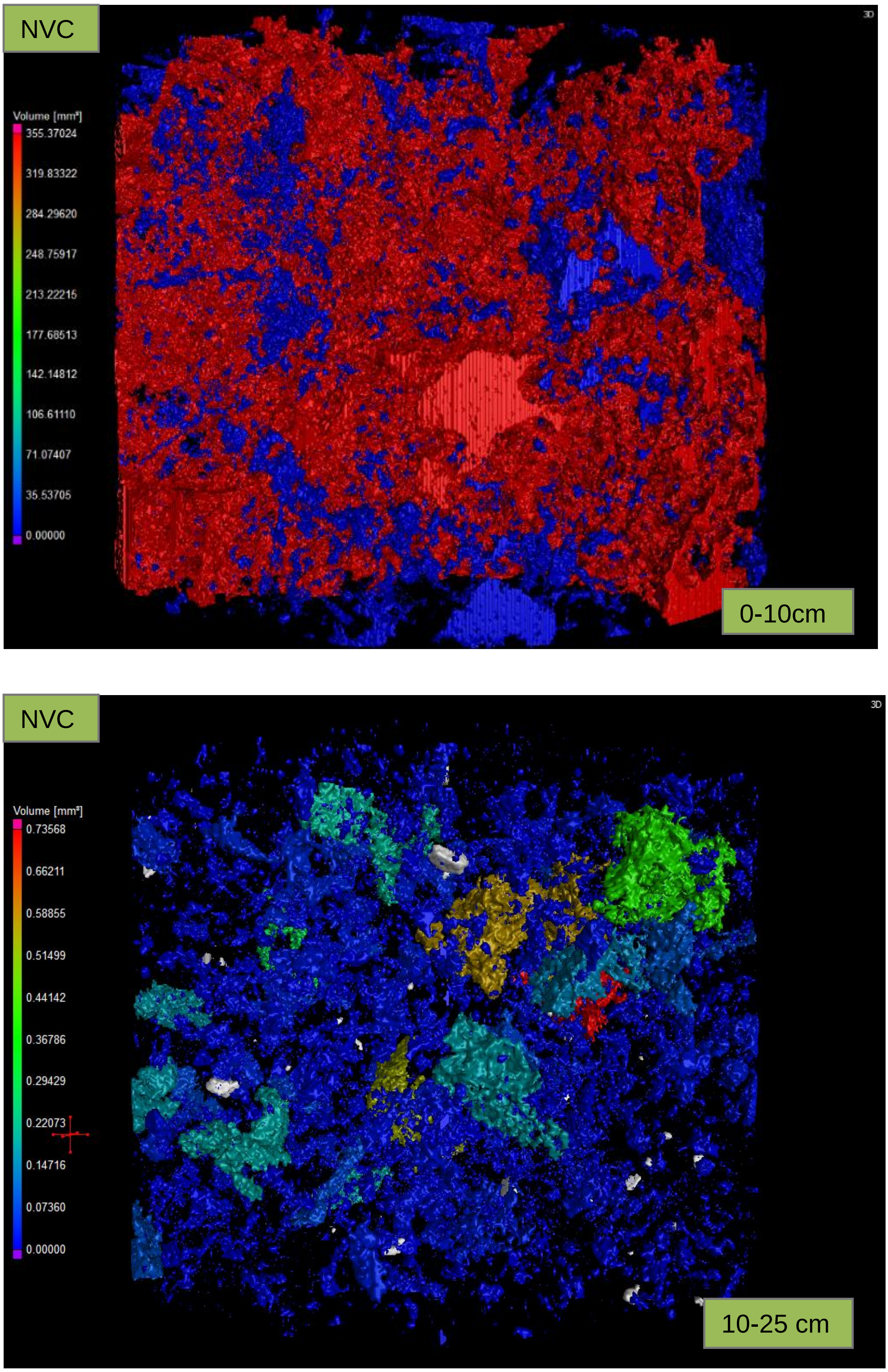


Figure 14: .Representative of pore system obtained from X-ray computed tomography in Hutton soil form from NVC area in two adjacent depth (0-10 cm and 10- 25 cm).

CHAPTER 5

5.0 DISCUSSION

A natural phenomenon of soil can be viewed using x ray computed tomography in both 2D and 3D, such visualization can permit morphometric characterization of soil and visualization of soil pore and crust developed within the soils. The results of this study have presented a visualization and quantification of 2D and 3D morphology of 4 different soils that have different morphological characteristics but susceptible to crust formation. Images were acquired after 30 minutes in each soil scan. Images acquired from CT allowed high quality visualization with minimum preparation (Le *et al*. 2019).

The results agree with those reported by Zhao *et al*. (2017). Who reported that it may have been due to increase in roots that causes voids, large cracks and large pores. A decline in total porosity with depth has been observed by another author such as Müller *et al*. (2018). It is evident that porosity in Dundee soils that has a sandy texture decrease in depth, however the pore diameter remains constant with depth which may indicate that the soil is uniform and there is high connectivity of between pore.

Shortlands soil form tomographs results indicate a decrease in porosity with increase in depth in both parameters. A decrease of 0.0503 mm pore diameter from 0.0549 mm shows a micro structural variation of soil. Crust are interconnected and are known to reduce water infiltration (crust is red in colour; black colour indicates pores/voids and various colour indicate different aggregate) see figure 6-14.

The size of sample enabled choice of RIO selection and select an area that is less disturbed to mimic the natural phenomenon of soils, consequently, there was limitation in time given by the facility to select multiple ROI for analysis. As a result, limitation was encountered again since some crust were separated from soil sample. Therefore, it was impossible to select a RIO that covered crust since they will be large voids in between and it will not mimic the natural phenomenon of soil (Figure 5). High resolution image acquisition was possible as the RIO was reduced, such can be viewed in comparison of Figure 5 and Figure 6.

The behaviour of the soil of all selected soil form in the present study was in line with those reported by Land Types Survey Staff .(2003), for example, during their analysis, Shortlands soil form was analysed for Particle Size < 2mm of sand and was reported to be 10.2% at top soil while, at second horizon started to be degrees and it became 1.5%. in the current study particles that are less than 20 µm at the bottom of the sample was 3.4496% and decrease to be 3.4079%. such microscopic variation can confirm the change of soil particles variation with a small microscopic area.

The images confirm that, Glenrosa soils have high crusts formed and few soil pores that are connected, and pore increase with soil depth. However, Dundee soil are deep and characterised by uniform horizon with continuous voids. Meanwhile, Hutton soils are characterised by crust with increase in voids and Shortlands are visibly crusted and increase voids with depth. The results show that the main body of all soils is dominated by Regular shaped aggregates.

The results support the hypotheses of the study, that soil structure can be studied using 3D X-Ray CT images and intact cores can be used to quantify the structure images resulting from crust formation. Contrary to the hypothesis associated with soil structure, other characteristics such as soil pore networks, pore connectivity were not identified due to limitation of resources.

The CT imaging technique enabled the view of accurate 3D images and relevant information such as pore volumes, pore diameter and shape of pore, mean voxel size are also acquired in single scan, compaction and tortuosity can also be identified with high quality and minimum sample preparation Le *et al*. (2019).

The results obtained in the study add value to existing knowledge of soil visual evaluation. The method produced aggregates visualization without disturbing the sample providing reference of photographs, evidence of biological activities (cracks) were present and sensitivity of soils such as cohesiveness was solved in showing the aggregates in tomography (Rabot *et al.* 2018). Previous research has focused on quantifying physical and structural soil properties Tseng *et al*. (2018). The results produced by the author suggested that it can be used to predict the influence of soil architecture, these results from this study demonstrated that x-ray CT should be used with other methods to understand the soil microstructure. For example, comparison of different tillage systems and their influence in the microstructure of soils.

The results in this study can be used to manage crusting problem by confirming that all studied soils, Hutton, Dundee, Glenrosa soils and Shortlands are prone to soil erosion and crusting development. Such information can be used on land use of that location recommending the use of conservation practices to minimize crust development, for example, using Cover crops, regularly monitoring Salinity and Sodicity in soil, selecting right tillage and always using plant residues to cover soil.

The results in Table 1 and 2 might suggest that the bigger the aggregate analysed, the greater the regular shape of aggregates. However, based on the findings of similar studies, a more plausible explanation is, the smaller the aggregate fragment is, the more rounded the particle shape is (Li *et al*. 2018). Furthermore, the results contradict with claim of Li *et al*. (2018) that suggested that the larger the soil aggregate is, the more irregular or elongated the particle shape is. Since all soil form are prone to crust development and soil erosion, farmers/ land users can be advised to limit burning, burying or removing plant residue; leaving the surface bare for long time without using mulch and farmers should stop soil distribution activities that destroys organic matter (Nciizah and Wakindiki. 2015).

The generalizability of the results is limited by lack of comparison of the soil around the sampling, nevertheless, it may mean that the results produced from this study may not indicate the overall soil form description. However, the reliability of this study is impacted by the distance of sampling to the area of analysis, since the core samples were moving a bit during transportation, the cores does not mimic 100% accuracy of the location. Due to lack of available data, the results cannot confirm the significant difference between VC and NVC soil in comparison to depth and the availability of micro-pores in the samples. Micro- pore analysis requires a selection of small ROI.

The choice of methodology were constrained by lack of time in MIXRAD facility, and also the availability of software such as ImageJ, Avizo, and Amira usually used to analyse the qualitative and quantitative statistical data, CT-Analyser (2013) was not available, statistical computing and graphics software were not employed to further investigate image data and calculations of pore connectivity (Du *et al*. 2019). However, it is beyond the scope of this study to apply statistical graphic software's and further analyse the Tomographs. Further research is needed to study detailed hydro physicals using X-ray μCT in order to understand and quantify essential ecosystem in different soil types. Further studies should consider the size of RIO, image pixel resolution, and sample storage during transportation and available software to analyse and study soil structure hydro physicals.

CONCLUSIONS AND RECOMMENDATIONS

X-ray computed tomography is an effective tool for visualizing hydro-physicals and micro-structure soil aggregates. This study quantified macro-pores, mesopores, micro-pores, pore shape and size of undisturbed samples from four soil forms. All soil forms were dominated by regular shaped aggregates and such aggregates are easy to be suspended and transported making them to be susceptible to water erosion. Therefore, crust formation affects soil structure degradation.

It is recommended that further studies be conducted using current raw data obtained from analysed soils in this study so that a concrete conclusion can be achieved. So that soil aggregates and volume of pores can be viewed and calculated including soil water retention and soil water movement in microscopic level, such information will boost in understanding micro-soil physical properties such as micro aggregates and micro pores.

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