



Discrimination of soil aggregates using micro-focus X-ray computed tomography in a five-year-old no-till natural fallow and conventional tillage in South Africa



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ABSTRACT

Soil use and management effect on soil microstructure was quantified. Soil aggregates ~10 mm diameter were collected from two fields: a five-year-old No-till natural fallow management (NTNF) and continuous cultivation (CC). The aggregate microstructure was determined with X-ray micro-focus computed tomography (X-ray μ CT) and image analysis was done using VGstudio MAX 3.0. Aggregate stability was higher in NTNF by \approx 5.7%. Micro-aggregates constituted \geq 80% of the aggregates in both treatments. Total porosity, microstructural pore properties (pore distribution, pore shape proportion) and visualization were similar in NTNF and CC. Despite the similarities, aggregates under NTNF had higher total number of pores. Therefore, managing soil through NTNF improve porosity even when the effect on the overall soil aggregation is not obvious. The study showed that aggregate stability is significantly linked to aggregate microstructure.

1. Introduction

Soil is a complex multi-component system with hierarchical organization and quality that can be explained by studying each component at a spatial configuration [1]. For instance, the effect of different soil use and management practices on soil behavior can be revealed by studying the spatial configuration of soil aggregates [2, 3, 4]. Aggregate stability tests commonly measured by methods such as that by Le Bissonnais [5] do not describe the status of aggregate architecture or give details on aggregation process [6]. Aggregate size, stability and pore size distribution within the aggregates are important characteristics of soil structure that influence the ultimate soil functions and behaviour. The microstructure of soil aggregates governs both soil stability and soil quality [7]. Consequently, examining the microstructure of soil aggregates, helps to understand the measured aggregation stability [7].

X-ray computed tomography (X-ray CT) is an excellent tool for studying the nature of soil components at a spatial configuration [8, 9]. Data obtained from X-ray CT can be used to relate soil components to soil behavior, processes and development [1]. X-ray CT offers a non-destructive way to characterize soil structure over a range of scales at high resolution [10]. The traditional methods like soil–water retention

method, which are commonly used around the world to study the macro porosity and pore-size distribution of soils, cannot offer details on distribution of pores larger than 300 μ m in diameter [11]. Computed tomography methods offer resolution of measurement even on a millimetre to micrometre-scale [12]. Thus, X-ray CT is a valuable tool for characterising pore-space from the macro-to the micro-scale [11]. In addition, X-ray CT offers suitable means of recording the three-dimensional form of soil structure [13], which allows complete visualization of many soil components and their arrangement [14]. Taina et al [1] and Kumi et al [9] previously summarized principles of X-ray CT.

X-ray CT was used to study soil structure attributes such as pore size, shape, pore distribution, pore connectivity and surface area both at macro- and micro-space [12]. In this experiment, agroforestry and grass buffers were established under rotational grazing and continuous grazing. The authors found macroporosity to be 13-times higher in buffers than pasture treatment. The increased macroporosity most likely increased soil water infiltration and reduced runoff, and increased gas exchange [12]. Vegetation restoration was found to enhance microstructure by significantly increasing total porosity, macro-porosity, and fraction of elongated pores, which are all essential to reduction in soil erosion and improvement of soil quality [7].

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Tillage effect on microstructure was discriminated using X-ray CT e.g. by Gantzer and Anderson [15], Ferro [16] and Pires [17]. Using X-ray μ CT, the application of no-till (NT) was found to have a better pore connectivity than conventional tillage (CnT) [17]. In addition, the use of CnT disrupts macropore structure, promoting pore class in the range 54–250 μ m equivalent diameter and soil erosion [16]. Conversely, Gantzer and Anderson [15] found CnT to have twice the number of macropores, > 500 μ m, than in the no-till treatment. The different results in the two studies might be due to site-specific conditions and management except tillage. Effect of compaction on microstructure was investigated using X-ray CT [18]. Authors found compaction to decrease porosity and macroporosity by 64%, number of pores by 71%, macropores by 69% and mesopores by 75% compared to non-compacted soil. The application of X-ray CT in soil science is in line with the statement made by editors of the Journal of Hydrology that “A new era of soils research calls for “structure-focused” efforts that is beyond the classical “texture-focused” stage” [19]. Numerous efforts have been made on studying the effects of land use and management on soil structure however, most of these studies have been restricted to a specific scale and data of the responses of soil structure at different scales is lacking [20].

Fallow management ensures recovery of soil fertility after continuous cropping [21, 22]. According to Jou and Lal [23], fallow practice can maintain soil physical properties and soil organic carbon (SOC) while CnT system leads to decline in SOC. Change in SOC has an impact on soil quality because SOC determines many soil characteristics such as nutrient mineralization, aggregate stability and water uptake [24]. Increases in soil microbial biomass and SOC, which are important driving features for aggregate stability [25, 26], were reported after implementation of fallow management compared to continual tillage [27]. Improvement in aggregate stability was reported after fallow management [27, 28] while a decline in aggregate stability was reported under continual tillage [29, 30, 31]. The effectiveness of fallow on soil quality and soil water status is determined by many factors ranging from weed control, fallow period and the type of fallow practice [32, 33]. The common fallow practice types include natural fallow and mulch fallow system [21] while weed control during fallow can be done with herbicides, tillage [33] or not controlled. Thus, variation in soil quality compared to continuous tillage system is expected from one fallow management to another. However, the effect of weedy or natural fallow management on soil microstructure is currently not well understood. CT scanning can, therefore, assist in clarifying soil structure dynamics under different degrees of plant presence i.e. weedy fallow and bare surface under continuous tillage (CC). It was, therefore, hypothesized that no-tillage natural fallow (NTNF) affects soil aggregation thereby altering soil microstructure and porosity. The objective of this study was to determine the effect of CC and NTNF on aggregate stability and the resulting soil microstructure and porosity using X-ray μ CT and image analysis.

2. Materials and methods

2.1. Soil use and management prior to sampling

In order to study the effect of post treatments of on soil aggregation like previous research [7, 34, 35], soil samples were randomly collected from two adjacent fields, of approximately 71 m \times 23.6 m area each, at the University of Fort Hare experimental farm (latitude 32°46'S and longitude 26°50'E at an altitude of 535 m). The farm receives an average annual rain of 575 mm and has a warm temperate climate with mean annual temperature of 18.1 °C [36]. The dominant soil type in the farm is of alluvial origin, classified as Haplic Cambisol [37]. One field was under continuous cultivation (CC) with maize while the other field was on No-till natural fallow (NTNF). Each treatment had been applied for at least five years prior to sampling. Under CC, moldboard plow tillage was applied at about 0.2 m depth followed by disking at summer maize season. Hand hoes were used to prepared seedbed in CC. Weeds were not

controlled in NTNF but under CC, weeds were controlled with atrazine herbicide and hand hoes during the growing season and with gramoxone herbicide [Paraquat as active ingredient] at 4 L/ha after harvesting. In the CC plot, fertilizer was applied at 90 N kg/ha. A third of the Nitrogen (N) fertilizer was applied at planting as a compound fertilizer (2:3:4 (30)) and the rest as limestone ammonium nitrate at 6 weeks after planting. Plant residues were removed after harvesting. Selected soil properties from both treatments are presented in Table 1.

2.2. Soil sampling and preparation

Soil samples were randomly collected from the top 0.1 m using a flat spade from each treatment and combined into five representative samples. Soil samples were transported to the laboratory in rigid containers to avoid breaking soil aggregates [38]. In the laboratory, the samples were spread on benches and air dried before analysis.

Soil chemical properties were determined using standard methods from air dried samples that passed through 2 mm sieve. Soil pH and soil electrical conductive (EC) were measured in 1:25 soil:water ratio using pH and EC electrode meter, respectively. Particle size distribution was determined using hydrometer method after oxidation of SOM with hydrogen peroxide (H₂O₂) as outlined by Gee and Or [39]. Walkely-Black method was used to determine SOC.

2.3. Aggregate stability

Aggregate stability was estimated by calculating mean weight diameter (MWD) using the fast wetting method described by Le Bissonnais [5]. Briefly, 3–5 mm air dried aggregates obtained by sieving soil aggregates through 5 mm mesh sieve, which was placed on top of 3 mm mesh sieve were oven dried at 40 °C for 24 h to bring them to a constant matric potential. A 5 g sample of aggregates was immersed in 50 ml deionized water for 10 min. A pipette was used to suck off the water. The soil material was then transferred gently to a 53 μ m sieve that was previously immersed in ethanol. The sieve was gently moved up and down in ethanol five times to separate the <53 μ m fragments from those which are >53 μ m. The remaining aggregates were collected on a 53 μ m sieve, dried in an oven at 105 °C, and their size distribution was measured by dry sieving with sieves with 2000, 1000, 500, 212, 106 and 53 μ m apertures to create seven aggregate classes namely: 2000–5000 μ m, 1000–2000 μ m, 500–1000 μ m, 212–500 μ m, 106–212 μ m, 53–106 μ m and <53 μ m. The mass of the <53 μ m fraction was calculated as the difference between the initial mass and the sum of the mass of the six other fractions. The aggregate stability was expressed as the MWD of the seven classes as follows: Eq. (1)

$$\text{MWD} = \sum_{i=1}^7 \bar{X}_i W_i \quad (1)$$

where W_i is the mass fraction of aggregate in the size class i with a diameter \bar{X} [5].

Table 1

Basic soil properties from continuous cultivation (CC) and No-till natural fallow (NTNF) site.

	CC	NTNF
Sand (%)	64.0 [±0.18]	62.0 [±0.18]
Silt (%)	12.0 [±0.08]	16.0 [±0.09]
Clay (%)	24.0 [±0.10]	22.0 [±0.09]
Soil organic carbon (%)	0.97b [±0.02]	1.15a [±0.03]
pH (H ₂ O)	7.27 [±0.08]	6.98 [±0.08]
EC (mS m ⁻¹)	44b [±1.00]	62a [±1.24]

Note: Values followed by the different letter within a row are significantly different at 0.05 level, Standard deviation (STD): [].

Table 2

Aggregate stability from continuous cultivation (CC) and No-till natural fallow (NTNF) site.

	MWD	Stability class
CC	0.40a [± 0.08]	Unstable
NTNF	0.42a [± 0.05]	Unstable

Note: Values followed by the same letter within a row are not significantly different at 0.05 level, Standard deviation (STD): [].

2.4. CT scanning and image analysis

Five soil aggregates of approximately 10 mm diameter from each representative sample were scanned with X μ CT at MIXRAD facility section of The South African Nuclear Energy Corporation SOC Limited (Necsa). Thus, a total number of 25 aggregates were scanned per treatment. The samples were scanned using a 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. Scanning parameters were set to 90keV/90 μ A to optimise penetration of X-rays through the soil aggregates. The scanning resolution was set at 18.9 μ m in order to visualise the soil microstructure. An aluminum filter was used to approximate a homogeneous X-ray beam spectrum of high X-ray photons by removing the lower energy 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°. One thousand projection images were obtained in the 360° at 2 sec exposure time for each projection. The scans were then reconstructed using Nikon CTPro software® (Nikon Metrology, Leuven, Belgium) and further analysed using VGStudio Max V3.0.0® (Volume Graphics GmbH, Heidelberg, Germany).

To avoid the edge effects, a region of interest of 52 ± 0.1 mm³ volume was selected at the middle of the 3D aggregates. Equivalent diameter was used to express pore sizes from the 3D aggregate. The pores were classified into seven classes: <50, 50–100, 100–200, 200–300, 300–400, 400–500 and >500 μ m [7]. Sphericity (S) was used to classify pores into three pore shape classes: regular pores ($S \geq 0.5$), irregular pores ($0.2 < S < 0.5$) and elongated pores ($S \leq 0.2$) [7]. The 3D sphericity was defined as the ratio of surface area of a sphere having the same volume as the object to the actual surface area of the object [40]. 3D total porosity was defined as the total number of pore voxels divided by the total number of volume voxels [16].

2.5. Statistical analysis

Analysis of variance (ANOVA) was performed using JMP® 13 [41]. Mean separations was done using the least significant difference method at $P \leq 0.05$.

3. Results

At the time of sampling, some soil properties in CC and NTNF fields were similar but others significantly different (Table 1). Soil texture was sandy clay loam and pH was neutral. Soil organic carbon and EC were

Table 3

Aggregate size distribution from continuous cultivation (CC) and No-till natural fallow (NTNF) site.

	Aggregate classes (%)								
	5000-2000 μ m	2000-1000 μ m	1000-500 μ m	500-212 μ m	212-106 μ m	106-53 μ m	<53 μ m	Macro-aggregates	Micro-aggregates
CC	4.87 ^a	2.79 ^a	4.18 ^a	24.65 ^a	32.14 ^b	11.20 ^a	20.16 ^a	11.85 ^a	88.15 ^a
NTNF	4.82 ^a	2.94 ^a	7.37 ^b	26.66 ^a	26.13 ^a	11.77 ^a	20.32 ^a	15.13 ^a	84.87 ^a

Note: CC aggregate classes STD range: ± 0.04 to ± 0.09 , NTNF aggregate classes STD range: ± 0.02 to ± 0.08 .

significantly lower in CC compared to NTNF treatments.

3.1. Aggregate stability

Aggregate stability was not significantly influenced ($P > 0.05$) by the two soil use and management practices (Table 2) except the distribution of aggregate size classes 1000 - 500 μ m and 212-106 μ m (Table 3). According to the Le Bissonnais [5] aggregates from both systems were unstable.

3.2. Soil aggregates visualization and pore size distribution

Indistinct soil aggregates microstructure morphologies were observed for both NTNF and CC aggregates (Fig. 1). Pore size distribution followed a similar pattern in aggregates from both treatments (Figs. 2 and 3). Aggregates from both treatments were mainly dominated by pore size class with a diameter of less than 50 μ m followed by pore sizes class diameter between 50 and 100 μ m, with pore size class of diameter greater than 500 μ m being the least dominant pore size class (Fig. 2). The NTNF aggregates, generally had more pores in each pore size classes. The NTNF pore frequency in pore size class of less than 50 μ m was almost double that of CC in the same pore class (Fig. 2).

Total porosity and fractions of pore shapes were statistically not different Pore class with diameter ≥ 500 μ m, accounted for more than 90% of the total porosity. The least porosity was for 400–500 μ m pore size class. Aggregate from both treatments were dominated by the fraction of regular pores, which accounted more than 95% of pore shapes while fraction of elongated pores formed less than 0.1% of pore shapes in both the treatments (Table 4).

4. Discussion

Soil use and management affects soil aggregation thereby influencing carbon sequestration and soil behaviour [42]. The effect of a five years no-till natural fallow (NTNF) and continuous cultivation (CC) on soil aggregation was studied. Aggregate stability is related to MWD [43]. The higher the MWD the more the aggregates are stable [5]. Accordingly, aggregate stability can be classified into five classes namely; MWD is >2.0 mm, very stable; 1.3–2.0 mm, stable; 0.8–1.3 mm, medium; 0.4–0.8 mm, unstable and <0.4 mm, very unstable. Thus, the results from both sites suggest that aggregates were unstable (Table 2), although aggregates under NTNF had significantly higher SOC. At the same site, Nciihah and Wakindiki [38] observed that the effect of soil organic matter was directed by the soil texture and clay mineralogy because their intricate association. Resultantly, both treatments were dominated by micro-aggregates.

Conventional tillage mechanically breaks down macro-aggregates into micro-aggregates [44]. It also disrupts the binding agents such as roots, fungal hyphae, and by-products of microbial synthesis and decay [45, 46]. So, the dominance of micro-aggregates under NTNF could be due to reduced amounts of binding agents as a result of diminished root activities in the rhizosphere [42]. Since it is generally agreed that macro-aggregates are formed and stabilized by biological factors, such as roots, fungal hyphae [45], in this study, the amount of weedy biomass in the NTNF was insufficient to cause significant input of binding agents into the soil. The findings from this study, however contradict that showed significant increases in MWD due to fallow management practice

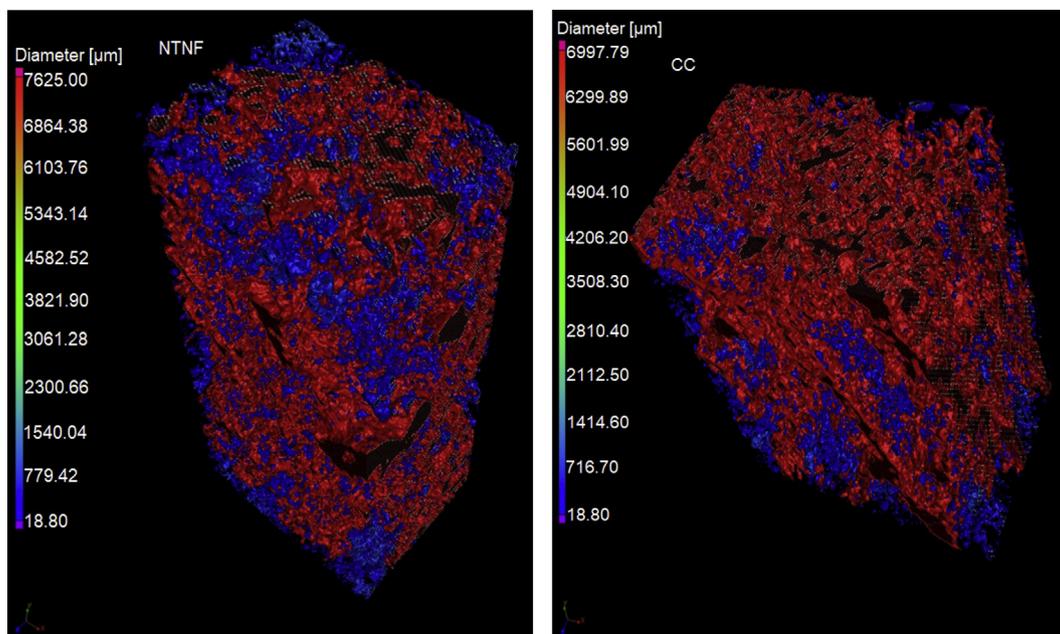


Fig. 1. Representative of 3D pore structure of soil aggregate from No-till natural fallow (NTNF) and continuous cultivation (CC).

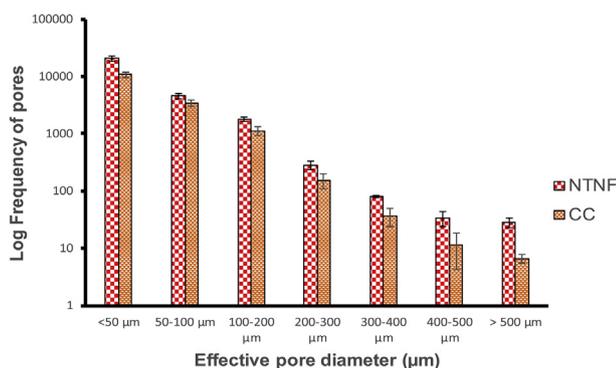


Fig. 2. Pore-size distribution frequency with error bars for soil aggregates from No-till natural fallow (NTNF) and continuous cultivation (CC) treatments.

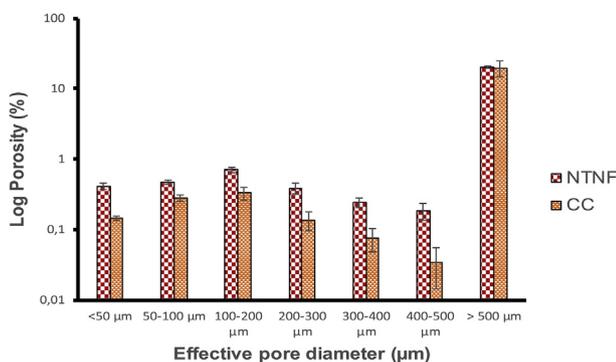


Fig. 3. Pore-size distribution porosity with error bars for soil aggregates from No-till natural fallow (NTNF) and continuous cultivation (CC) treatments.

[47]. Nonetheless, benefits of fallow management are usually observed over long periods of times [47] unlike in the short fallow period of 5 years in this study. In a study of the impact of natural fallow duration on top soils characteristics of a Ferralsol in Cameroon [47], concluded that it took a minimum of 10 years for the soil under natural fallow to recover its optimum equilibrium inclining towards conditions under the virgin forest.

Table 4

CT measured porosity and pore shapes from continuous cultivation (CC) and No-till natural fallow (NTNF) site.

	CC	NTNF
Total porosity (%)	20,74a [\pm 1.61]	22,34a [\pm 0.92]
Fraction of regular pores (%)	96.31a [\pm 0.72]	96.85a [\pm 0.51]
Fraction of irregular pores (%)	3.68a [\pm 0.71]	3.13a [\pm 0.49]
Fraction of elongated pores (%)	0.01a [\pm 0.01]	0.02a [\pm 0.01]

Note: Values followed by the same letter within a row are not significantly different at 0.05 level of significance, Standard deviation (STD): [].

The visualization of 3D aggregate supported the MWD results by revealing few differences in aggregates from both treatments showing that the application of no-till natural fallow didn't have much impact on aggregates microstructure. The quantity analysis of aggregate pore system (e.g. total porosity, pore size distribution and frequency) treatment showed that NTNF aggregates had a more porous structural system. The NTNF had a slightly higher macro-porosity (>500 μm porosity), which allows for easier movement of water, solutes and nutrient [48]. The slightly higher total porosity under NTNF might be attributed to the proliferation in roots associated with permanent vegetation [49, 50] during the fallow period. The root growth and activity of permanent vegetation under NTNF might also attribute to the higher number of pores [51] compared to CC site. Thus, better transportation is expected under NTNF compared to CC site. The 3D aggregate and distribution of pores show that soil structure from both sites is closely related. Regarding pore shapes, the fractions of elongated pores, which are crucial for soil water and gas transport [7, 52], were found to be less than 0.1% under both treatments. The less fraction of elongated pores show that there is high potential of soil erosion from both treatments. This is also supported by low aggregate stability from both treatments.

5. Conclusion

X-ray CT and digital image analysis successfully provided insight on the microstructure of soil aggregates. It allowed for investigation of the effect of NTNF and CC on soil aggregation processes in its early stages. Whereas the overall aggregate stability may not respond to NTNF and CC within a five year period, NTNF can significantly alter soil porosity. The study also demonstrated the link between aggregate stability and

aggregate microstructure.

Declarations

Author contribution statement

M.E. Malobane: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

A.D. Nciizah, I.I.C. Wakindiki: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

F.N. Mudau: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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