Instrumental Opportunities of X-ray Computed Tomography on Soil Compaction Characterization to Sustainability in Agricultural Systems

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ABSTRACT

The technologies of precision agriculture have allowed collecting information with better fidelity from soil properties. In this modality of management, it takes into account the segmentation of a given agricultural area in a number of small cells and the use of inputs is performed with variable rates, leading to a low impact on soil natural resources, mainly because only the local needs are considered. This management technique leads to better sustainability in the use of agricultural soils. In this context of interest for precision farming, it is found the use of X-ray computed tomography that has been useful, since the first work published in 1982. This paper discusses the different modalities of X-ray tomography instruments and opportunities for the establishment of direct use on the field that allow the mapping of soil compaction, which has an important impact on both the movement of water and nutrients, and also on plants rooting.

Keywords: X-ray tomography, precision agriculture, sustainability, agricultural soil, compaction, Brazil.

1. INTRODUCTION

The constant growth of world population is increasing demand for food and, consequently, an increasing demand of agricultural activities. On the other hand, to increase the production it is, generally, either necessary deforest, which goes against the ecological concern or use with priority a major approach of science and technology on the field. The intensified use of land, the environment degradation and the planet climate changes are requiring technologies that manage and sustain the use of soil and water resources. All these factors make the agriculture sustainability crucial to the balance between the pressures on these resources and the growing agricultural productivity.

The sustainability of agricultural systems will be built by combination of scientific knowledge about the physical and chemical properties of soil and water resources with a philosophical and

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cultural change in the use of these resources economically. To increase agricultural production, with technology and scientific support, the farmers must: (i) to improve the quality of agricultural lands, (ii) to expand, to maintain, and to enhance production on lands previously viewed as “marginal”, such as steep lands and semiarid tropics, and (iii) to restore degraded lands. The latter commonly has problems as soil compaction, loss of soil organic matter, reduced activity by soil organisms, nutrient deficiencies and imbalances, as well as erosion (Committee on International Soil and Water Research and Development *et al.*, 1991).

It is not a simple task to recover a degraded soil. The soil is a complex system and the main reasons for such complexity are its natural porous medium formed by the action of climate and microorganisms. As a result of those processes, soil is highly variable and heterogeneous in contents, which are different minerals and organic materials in state of decomposition. The soil porosity is responsible for transport processes and water storage, influencing this way the adsorption and reactions of solutes in soil solution (Crestana and Vaz, 1998). When the soil porous medium is compacted, it increases the resistance of roots growth, reduces the water infiltration into the soil, causing water and nutritional plants deficiency. Consequently the roots grow superficially and increase the risk of erosion (Gonçalves *et al.*, 2006). It is crucial to know the soil compaction effects to improve soil management and, this way, increase the crop production.

The aim of this paper is to present methods and opportunities of X-ray computed tomography and its application on soil science. Also a discussion in the direction of what sense they can help and improve the soil analysis research. Furthermore, the instrumental applications of X-ray computed tomography is presented in determination of soil physical features were included to exemplify its uses for volumetric water soil content, the growth quantification of plant roots, and the analysis of earthworm burrow system for soil structure.

2. BASIC PRINCIPLES

The word tomography is composed by two Greek words: *tomo*, meaning slice or section and *graphy*, meaning to write or display. The tomography is a three-dimensional image of the internal structure of the sample under analyses. It is based on a large number of transmissions measurements of the attenuation of radiation beam.

There are four main effects that occur between X-rays and an irradiated sample: Raleigh (coherent) scattering, photoelectric effect, Compton effect and pair generation (Duliu,1999). The attenuation of X-ray, due to passage through the sample, following the Beer’s law:

$$I = I_0 . e^{-\mu x} \qquad (1)$$

where I_0 is the photons that reach the sample; I is the photons that crossed the sample; μ is the linear attenuation coefficient of sample; and x is the sample width. The linear coefficient μ depends of effective atomic number Z_{ef} and the density ρ of sample under analysis, as the semi empirical relation presents (Jacobs *et al.*, 1995):

$$\mu = \rho\left(a + \frac{b.Z^{3.8}}{E^{3.2}}\right) \qquad (2)$$

where *a* represents the nearly energy-independent Klein-Nishina coefficient and *b* is a constant. The first term in equation 2 is related to Compton scattering and the second term is related to photoelectric absorption. The X-ray energy range between 30 and 200 keV, only coherent scattering, photoelectric and Compton effects occur. The pair production occurs at energies greater than 1022 MeV. In the case of predominance of the Compton effect, the linear attenuation coefficient μ depends more of the density of the sample than its chemical composition. In contrast, the photoelectric effect depends more of the chemical composition of the sample. Experimentally, it is possible collect photons and analyze them, placing detectors in various angles around the irradiated sample (Cesareo *et al.*,1992). A single process and its different cross sections are characterized by energy and intensity of various photon peaks. The information about the sample can be deduced by the characteristic X-rays emitted, that is, the energy, or even the intensity of scattered radiation. A monochromatic photons beam (fig. 1) which the spectrum is composed by: (i) only an energy peak E_0 in transmission mode; (ii) an energy peak E_0 due to elastic scattering; (iii) an energy peak E_C due to Compton effect; and (iv) various energies peaks due to photoelectric effect.

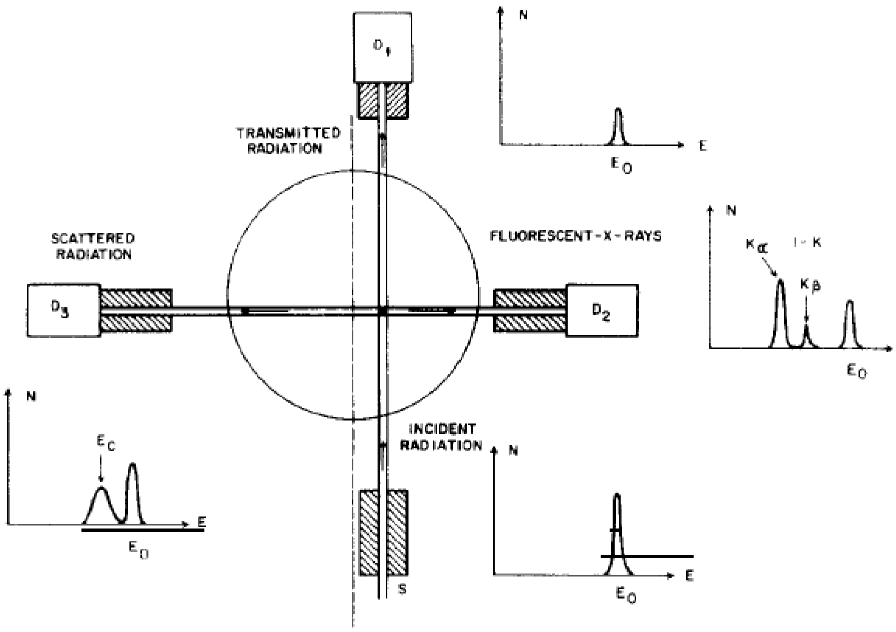

Figure 1. Interaction of monoenergetic radiation with matter (Cesareo *et al.*, 1992).

3. X-RAY TOMOGRAPHY OPPORTUNITIES IN SOIL SCIENCE

The X-rays have been a useful analysis tool since your first use: an examination of a fossil (Brühl, 1896). The major X-rays advantage is furnish quantitative as well as qualitative information about local density from samples in non-destrutive manner, i.e., the object maintain its structure or properties during the analysis.

The union of X-ray physics, detector technology and mathematical reconstruction theory allowed the development of a pioneer technique called computer assisted tomography (CAT), which was published by Godfrey N. Hounsfield (1972). The CAT allowed show three-dimensional image of the internal structure of the object under examination, in a nondestructive manner. This is possible using measurements of the attenuation between the radiation and the material in which the object is composed. Initially, the CAT was applied to medical diagnostic, reducing the necessity of exploratory surgery. In that same year, Allan M. Cormack (1972) published a method of reconstruction of densities from their projections with applications in radiological physics and in 1979 both Hounsfield and Cormack received the Medicine Nobel Prize.
In 1982, Petrovic and collaborators analyzed the CAT response near the upper limit of the measurement range where denser materials are located. They used soil and glass bead-air filled sphere as samples with a good three-dimensional spatial resolution from 1.25 by 1.25 by 2 mm^3 to 6.4 mm in diameter by 2 mm. These samples varied in bulk density from 0.14 to 1.64 g/cm^3 (Petrovic *et al.*, 1982). After these pioneer results, some trends were appearing with good results in soil science. Some examples are the study of volumetric water soil content and bulk density of soil columns, the growth quantification of plant roots and the analysis of earthworm burrow system for soil structure.
Hainsworth and Aylmore (1983) and Crestana and collaborators (1985) used an X-ray CAT scanner to measure soil water content and the motion of water in soil in three dimensions. It becomes possible studies of soil-plant water relations. The study of soil compaction commonly uses values of dry bulk density and total porosity. These physical features of soil interferer directly water circulation around plant roots which consequently prejudice the plant nutrition. Crestana and collaborators (1986) showed the usefulness of CAT miniscanner with a secondary target coupled to the X-ray tube to select the optimal energy of the radiation to obtain the best soil analysis conditions. Cruvinel (1987) developed an inexpensive homemade X-ray and gamma-ray minitomograph for soil science analysis. Phogat and Aylmore (1989) proved that the attenuation coefficient of soil and the macroporosity such as the total soil porosity had a strong linear correlation ($r^2 = 0.995$). Cruvinel *et al.* (1990) have shown the calibration process for both soil bulk density ($r^2 = 0.997$) and moisture ($r^2 = 0.970$) measurements with the use of the computerized minitomograph scanner. Grose and collaborators (1996) used a CAT to assess the spatial examination of the response of soil water to environmental treatments of the soil-root system and the observation of the effect of the spatial heterogeneity of volumetric water content upon fungal growth in the soil. Olsen and Børresen (1997), to reduce problems with soil erosion in Norwegian soils, used an X-ray CAT to analyze the effect of an increased number of macropores on solute infiltration between soil with conventional tillage practice and soil with reduced tillage. The results shown that the soil with reduced tillage (rotavating) the density is roughly uniform and in the underground the macroporosity was higher on rotavated than ploughed soil, i.e., the ploughing increases compaction compared to rotavation. Macedo and collaborators (1998) constructed a microtomography for soil non-invasive investigation in microscale of at least 100 μm and it was possible to observe grains of densities up to 4.5 g/cm^3. In 2000, it was published a new approach in tomographic instrumentation based on dual-energy Compton scattering (Cruvinel and Balogun, 2000). The results of this new tomography showed a linear relationship independent of soil aggregate sizes with regression coefficient better than 0.95 for bulk density and 0.70 for water content.

Rachman and collaborators (2005) used an X-ray tomography to characterize macroporosity of soil under perennial grass hedge system. The presence of grass in a watershed may reduce the water runoff and soil erosion because modify partially the soil macroposity. That research showed that grass hedges would significantly increase soil macroporosity as compared with traditional row crop management and indicated that using fractal dimension was useful to describe soil porosity values. To analyze soil bulk density, Pedrotti and collaborators (2005) compared both the volumetric ring technique and X-ray CAT methods using six different tillage systems for a Planosol of Pelotas, RS, Brazil: (i) irrigated rice cropping system (1 year of rice crop followed by 2 years of fallow land); (ii): continuous rice cropping system (conventional tillage); (iii): rice-soybean-corn rotation system (conventional tillage); (iv): rye-grass-rice rotation systems (no-tillage); (v): soybean-rice rotation system (soybean under conventional tillage in the first year rotated with rice under no tillage); (vi): fallow land – control treatment. The results showed that the tomography was more detailed and precise to determine soil bulk density than volumetric ring technique. The tillage systems (iii) and (iv) presented the most homogeneous and heterogeneous soil bulk density values respectively. The tillage systems (iv) and (v) had better soil physical conditions in terms of soil density, (ii) contributed to the physical degradation of the soil by compaction of soil layers.

In 2007, Scharader and collaborators assessed the soil structural differentiation around earthworm burrows by means of X-ray tomography and scanning electron microscopy (Sharader *et al.* 2007). Cylindrical macropores, called of drilosphere, are made by burrowing activity of earthworms. For their study, Schrader used four artificially repacked soil cores with 2.17% of organic matter and inoculated, in each core, one adult individual of the earthworm species *Lumbricus terrestris* and incubated by 70 days. These cores were compacted vertically by hydraulic press at a pressure of 250 kPa and all cores were analyzed by means of X-ray tomography. The results showed a total soil volume calculated for the drilosphere of 53 cm^3 per scan slice under uncompacted conditions considering a drilosphere radius of 2.2 cm. The authors highlight that the burrowing activity increases the soil heterogenisation which increase the soil stability against pressure loads and consequently improve the conditions for plant growth.

Macedo and collaborators (2007) used the X-ray minitomography, developed at Embrapa, Brazil, to analysis a dusky red latosol soil from Cascavel-PR region. The mass attenuation coefficient of the samples obtained was 0.3993 ± 0.0047 cm^2/g. The authors highlighted that the structures considered compact showed lower standard deviations, confirming its homogeneity. Furthermore, the samples showed no compact showed larger standard deviations, consistent with the variability characteristic of these structures (fig. 2).

To visualize better the reduction of macro-pore structure by soil compaction, Schäffer and collaborators used an X-ray microtomography and image processing to study the soil morphology and provided valuable indices for assessment of macro-pore structure and changes induced by compaction (Schäffer *et al.*, 2007). The results showed a macro-porosity reduction of roughly 20% after two passes and of 74% after 10 passes. They complement the last research with two other scientific papers: (i) one to study the mechanical stability of repacked soil and deformation of different types of macro-pores (Schäffer *et al.*, 2008a) and (ii) other to analyze the morphology of macro-pore stability in undisturbed and repacked soil (Schäffer *et al.*, 2008b). In the former research, they observed that cylindrical (bio)pores, which are made by earthworms, were more stable than interaggregate pores, i.e., are much less sensitive to compaction than interaggregate pores. In the latter research, they observed that with increasing trafficking intensity the macro-porosity and connectivity density decreased, while the mean pore separation increased. Thus, they concluded that the loads involved in cultivation of restored soils should be gradually increased over longer time periods with unloading between events. These actions give the soil water sufficient time to re-equilibrate and minimize the soil compaction.

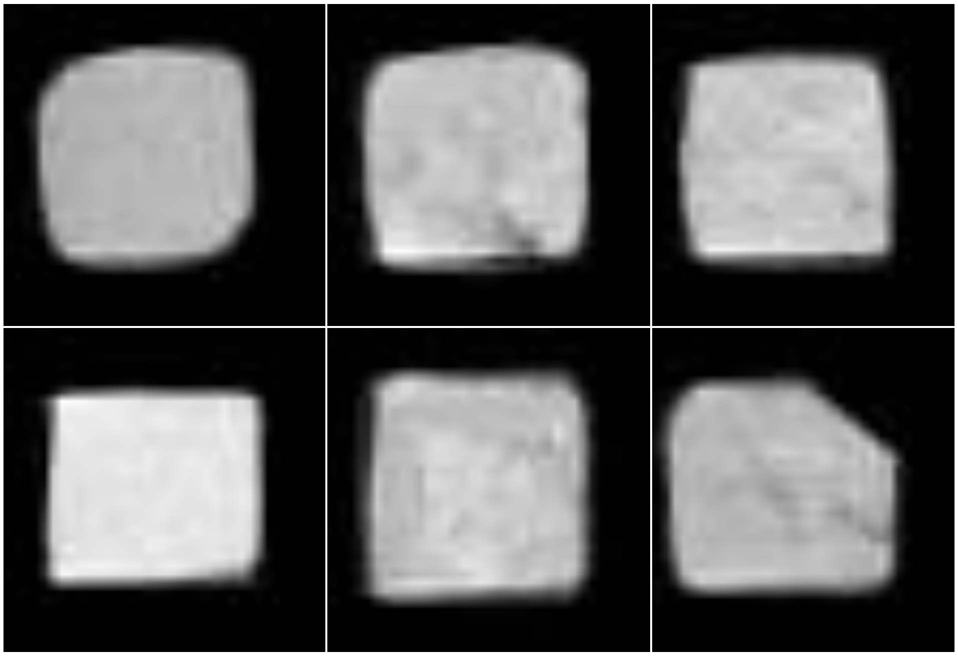

Figure 2. Tomographic images from dusky red latosol samples collected from Cascavel/PR (Macedo *et al.*, 2007).

In 2008, Lee and collaborators published a scientific paper to evaluate the use of a High-Resolution Computed Tomography (HRCT) to characterize surface seals through the pore distribution and cumulative porosity (Lee *et al.* 2008). In their experiment, the silt loam soil was used and treated with anionic polyacrylamide (PAM) or untreated and the simulation of rainfall had durations of 7.5, 15, 30 and 60 minutes at 55 mm/h rainfall intensity. The results obtained about modal pore-size frequency with $1x10^{-5}$ mm^3 pores, for soil treated with PAM, showed reductions from 992 to 812 pores between 7.5 and 60 minutes of rain and for untreated soil were reduced from 649 to 217 pores in the same conditions. These results showed that HRCT was a useful tool to evaluate soil surface sealing thorough of characterization of modal pore-size. Modolo and collaborators (2008) used the X-ray computed tomography with milimetric resolution to determine the soil-seed environment in tillage system, immediately after soybean planting. The methodology used was a scheme of subdivided parcels of three levels of soil water content of 0.27, 0.31 and 0.36 kg/kg and the subparcels of four load levels, applied by wheel compactor, of 0, 50, 90 and 140 N with four repetitions. The results showed that the biggest densities were observed below 10.0 cm depth in all treatments studied, i.e., below the depth sowing line. Although not affecting the mean density of soil in seed region, the authors highlight that these results can affect the crop root development, concentrating the roots in soil surface.

To evaluated water drawdown patterns in multiple-root systems, Hamza and collaborators compared water transpiration patterns estimated by X-ray computed tomography (CT) with traditional gravimetric method and evaluated the effects of variability spaced multiple root systems on soil water content and corresponding water content gradients (Hamza *et al.*, 2008). The results showed a water uptake, estimated by tomographic images, of 27-38% lower than the gravimetrically method, although it was found a good relation ($r^2 = 0.97$) between them. The authors explained that this difference is attributed to lower water uptake for upper 30 mm layer, where the measurements did with CT method was taken, than lower layers due to differences in root density.

Laia and Cruvinel (2008) used a discrete Kalman filtering together a neural networks to process a set of soil science tomographic projections, which was disturbed by noise varying in time and space. The validation was based on ISNR (Improved Signal to Noise Ratio) and the produced images were generated using a filtered backprojection algorithm. The best result was the discrete Kalman filter together a neural network, reaching a signal to noise ratio of 8.99 dB.

In 2009, Papadopoulos and collaborators compared stable and unstable soil aggregates from organically and conventionally managed soil, using an X-ray micro-CAT, to determine the role of management in aggregate stability (Papadopoulos *et al.*, 2009). The results showed that organic soils were more stable than conventionally managed soils, for a brown soil of silt clay loam. The organic matter inside soil aggregates of size > 0.3 mm was the binding agent between smaller aggregates and larger aggregates or small aggregates containing most of the organic matter were bonded together, forming stable macro-aggregates, giving resistance to soil to breakdown by slaking and providing an escape route for entrapped air.

The researches presented shown instruments and methods that restore or maintain the best soil condition, allowing the increase of plant growth performance.

4. CONCLUDING REMARKS

Among the papers selected for this characterization on the state of the art in the use of X-ray tomography for compaction characterization and sustainability in agriculture, it is fundamental to consider that: 92% of the reviewed applications are related either X-ray CAT of direct transmission (conventional, high, ultra and micro resolution) for soil science. The other parcel is related to the reviewed papers and application based on Compton scattering techniques. The soil compaction was studied for 72% of the authors and roughly 72% explained the importance of agricultural sustainability for increasing production. The instrumental opportunities were presented by 32% of authors using new analysis methodologies and X-ray tomography instruments. Also, it was studied and compared by different authors others agricultural systems (44%) related to sustainability and the importance of these scientific researches for precision agriculture (68%).

As a function of this analysis, it is important to take into account the opportunities in X-ray tomography and its different modalities for further applications in soil sustainability. Some of them are related to soil compaction due to load increasing by heavy machinery, trampling by livestock, the surface seals by rainstorms, as well as irrigation drops, and others. On the other hand, the major uses of such technique were related in the reported papers as laboratory analyzes. Therefore, the opportunities for its use direct on the agricultural field can be consider a good strategic point for future applications related to sustainability studies and agricultural development.

5. ACKNOWLEDGEMENTS

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