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Foreword

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Soils and their protection have been recognised of paramount importance by the Food and Agriculture Organization (FAO) by declaring 2015 as the International Year of Soils (Martín *et al*. 2017). Soils of natural and managed ecosystems deliver several fundamental ecosystem services which, according to the Millennium Ecosystem Assessment (2005), include provisioning services (e.g. production of food, fibre, fuel), regulating services (e.g. contaminant filtering, carbon sequestration, erosion control, flood protection), cultural services (e.g. recreation, tourism) and supporting services (e.g. nutrient cycling processes) (Schwilch *et al*. 2016).

The links between soil-related ecosystem services, soil functions and properties have recently been reviewed by Adhikari and Hartemink (2016). Depending on the dynamic interactions between physical, chemical and biological properties, soils generate a multitude of soil functions, which in turn support the delivery of ecosystem services. Among the key soil properties and functions identified by these authors, many of them are soil structure-dependant. Nowadays, it is generally assumed that all processes in soils are directly or indirectly dependant on soil structure (Martín *et al*. 2017). Indeed, soil structure affects retention and availability of water and nutrients, heat and air transport, root penetration, and in turn, chemical and biological soil properties (Rabot *et al*. 2018).

In the last decade several Special Journal Issues have been dedicated to new techniques and methods to advance the study of soil structure, soil functions and their interactions. There is no research field dealing with the relations between soil structure with abiotic (e.g. water, gas, particles) or biotic (e.g. roots, microorganisms) factors, where X-ray computed tomography (CT) has not been widely applied in the last twenty years.

The special publication of the Soil Science Society of America (Anderson and Hopmans 2013) 'Soil–Water–Root Processes: Advances in Tomography and Imaging' emphasised the role that X-ray CT and other imaging techniques have played during the last 20 years in the study of soil and root interactions. In Geoderma's Special Issue 'Structure and function of soil and soil cover in a changing word: characterization and scaling' (Martín *et al*. 2017), authors presented research on the parameterisation of structure being scale-dependent and examples on how structure is related to processes in soils. The role of different 3D high resolution imaging techniques along with advances in imaging processing that allow visualising water and transport processes in soil were reviewed in the special section 'Non-invasive imaging of processes in natural porous media' published in Vadose Zone Journal (Li *et al*. 2018). The breakthrough role of X-ray CT in the understanding of the growth and activity of microorganisms in soils and sediments was highlighted in the special issue 'Elucidating microbial processes in soils and sediments: microscale measurements and modelling' published in Frontiers in Microbiology (Baveye *et al*. 2018).

This recent rich publishing activity, as also evidenced by an analysis of papers published on the topic (Fig. 1), clearly demonstrates the wide interest in X-ray CT applications and the continuous and rapid advancement of imaging techniques.

In comparison to the papers published only six years ago in Anderson and Hopmans' (2013) Special Issue, impressive advancements have been made in both X-ray CT technology and image processing. This highlights the potential that these techniques, with the exponential improvements in the capabilities of X-ray CTs (e.g. with regard to resolution, power, and speed) and imaging approaches, can serve as common ground for interdisciplinary studies of the complex nature of soils.

PROTINUS (PROviding new insighT into INteractions between soil fUnctions and Structure) was a project funded between 2014 and 2018 by the European Union's Horizon 2020 research and innovation programme. It aimed to develop new experimental, imaging and modelling approaches in order to evaluate the impact of soil structure on soil functions. PROTINUS assembled a multi-disciplinary team that combined expertise in soil physics, biology and chemistry, as well as image acquisition and analysis and numerical modelling.

A selection of the project's results is presented in this Special Issue along with other related studies. The 14 papers of this Special Issue contribute to improving current approaches of characterising soil structure and its evolution with internal or external factors as well as discuss the effect of soil structure on functions associated to storage and filtering of water, mass and gas transport, nutrients cycle and habitat for biological activity. The scale investigated ranges from micropores to macropores, as in these papers the main tool used to image soil structure is X-ray CT at micron resolution.

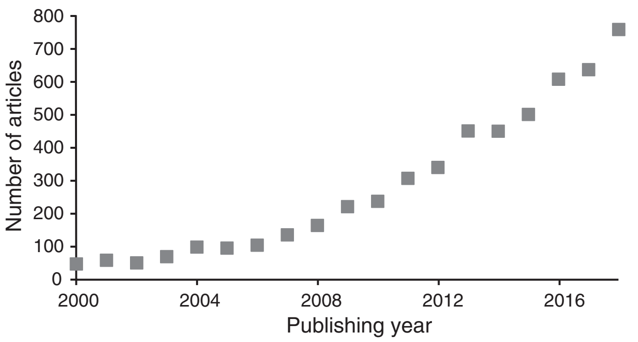

Fig. 1. Evolution of the number of journal articles including the terms 'X Ray CT and soil science' from 2000 to 2018. Source: Scopus, Elsevier, accessed 30 July 2019.

The papers are arranged in five sections: a methodological section, followed by a section on the studies of soil structure characterisations and three sections on the links between soil structure and physical, chemical and biological functions.

The first two papers describe the development and application of new methodologies related to the use of X-ray CT in soil sciences, a novel image segmentation technique and a new approach to visualise the distribution of particulate organic matter (POM) in soils are introduced. Several image processing steps are necessary to obtain parameters quantifying soil structure from X-ray CT 3D reconstructions. The choice of the image processing techniques will impact the resulting pore network. In particular, the segmentation to distinguish the pores from the solid is a crucial step (Smet *et al*. 2018). Azhar *et al*. (2019, this issue) provide an automated image segmentation strategy, use more robust than current state-of-the art methods. Soil organic matter is a key component of soil structure and an integrative indicator of land degradation. Piccoli *et al*. (2019, this issue) demonstrate that, thanks to the use of contrast agents, POM can be discriminated from the mineral fraction and its content successfully estimated.

In the second section of this Special Issue, soil structure evolution due to internal and external factors is characterised by means of X-ray CT and other imaging techniques. Soil structure is a dynamic property at different time scales and evolves with pedogenesis, root growth and different soil management practices. Amato *et al*. (2019, this issue) show that mucilage produced by myxodiaspores during seed germination alters soil structure and strongly binds soil. This is a transient but crucial time of crop production when the soil is totally or partially bare and soil stability depends on the relation between germination mechanisms and microorganisms. At larger time scale, Pogosyan *et al*. (2019*a* and 2019*b*, this issue) studied two types of subsoil horizons: one indurated subsoil from volcanic origin (Tepetates) and one high density horizon from a Luvisol (fragipan). These hard layers usually prevent root growth and water infiltration but little is known about their genesis. The 2D and 3D quantitative studies of the pore spaces show that pores of different sizes were formed at distinct stages: the small homogeneously distributed pores of the Tepetates were formed during the primary compaction, and large crack pores appeared later, while the clay coating infilling the cracks participated in a secondary compaction. The pore system of the fragipan is heterochronous: the mainly closed micropores were formed at the time of structural collapse while fissures appeared later.

In the third section of this Special Issue, the authors demonstrate how X-ray CT data can improve our understanding and modelling of hydrodynamic functions. Shiota *et al*. (2019, this issue) predict the drainage water retention curve by applying the voxel percolation method (VPM). VPM is a morphological approach under the assumption of capillary-dominated quasi-static flow. X-ray CT was used during a drainage experiment. The resulting images were segmented for solid, air and water phases. Permeability is another key soil function that is dependent on soil structure. Ortega Ramírez *et al*. (2019, this issue) compute the permeability by solving the Navier-Stokes equation into the 3D structure of Fontainebleau sand and virtual pack of spheres obtained at different resolutions. The conflict between the need of good resolution, the computational power requirement and the size of the sample increases the difficulty inherent to direct numerical simulation in real 3D porous structure. Müller *et al*. (2019*a*, this issue) found that structural parameters derived by X-ray CT were significantly related to indicators of preferential flow and that they can predict solute transport. In soils under different land uses and anthropogenic pressures, Yi *et al.* (2019) also found significant positive influence of soil macropore properties derived by X-ray CT on the pore water velocity or the solute dispersion coefficient.

The subtle interactions between soil structure, chemical properties and management were investigated in the fourth section. Indeed, agricultural management such as tillage, irrigation, crop type or animal treading modifies soil structure. Andosols are characterised by unique soil physical properties such as high water retention capacity, low bulk density and high permeability due to the presence of amorphous compounds that can be lost by inadequate agricultural practices (Duwig *et al*. 2019, this issue). Baniya *et al*. (2019, this issue) and Müller *et al*. (2019*b*, this issue) found that pore structural parameters derived from X-ray CT, were affected by compaction and that these allowed a fair prediction of several important mass transport parameters such as saturated hydraulic conductivities, soil-gas diffusion coefficients and soil-air permeabilities.

Soil structure is also affected by compaction, for example through grazing of crops *in situ*. This modifies soil aeration conditions and can lead to high emissions of nitrous oxide and leaching of nitrate to aquifers (Thomas *et al*. 2019, this issue).

Soil water repellency (SWR) is another transient process linked with soil structure through microbial activities. SWR implications on soil properties were addressed in the last section of this Special Issue. Some enzymes activities were strongly correlated with the development of SWR and could help the development of treatments to remediate SWR and improve water infiltration and soil water storage (Simpson *et al*. 2019, this issue).

These results of the PROTINUS project plus the reinforcement of international research networks through the project set the base for future investigations of soil structure and soil functions in a world under much climate and anthropogenic pressure. Soils are among the key resources to overcome some of the threats humanity is facing, such as improving soil management to ensure food security for the world's rising global population and increasing carbon storage in soils to lower the threat of climate change (Schlesinger and Amundson 2019). It also demonstrated that X-ray CT may serve as a common ground for interdisciplinary studies in soil soils, combining expertise in research fields only apparently far from each other.

Conflict of interest

The authors declare no conflict of interest

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