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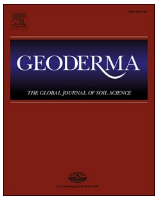

Zero tillage has important consequences for soil pore architecture and hydraulic transport: A review

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ABSTRACT

Following the adoption of zero-tillage (ZT) from conventional tillage (CT), the soil pore network undergoes immediate and significant changes. As soil remains undisturbed for an extended period, a soil structure emerges that is primarily generated and stabilised by both biotic and abiotic processes. There is limited understanding concerning how the adoption of ZT influences the soil porous architecture and associated soil hydraulic properties, and specifically over what timeframe these changes occur. Since a previous synthesis of such information over 20-years ago, there has been a substantial number of new investigations aimed at addressing this knowledge gap. Here we review 34 papers that illustrate ZT can influence porosity depending on soil texture, pore size class, depth and time, and also influence important transport mechanisms likely to impact the fate of agrochemicals in soils. We found decreased macroporosity in surface layers of soil under ZT when compared with CT. In addition, soil pore connectivity tended to increase in soil under ZT though the associated effects on hydraulic transport were less clear. Our investigation reveals the value of a prospective examination of an evolving ZT pore network both visually and functionally across temporal and spatial scales. We also highlight the necessity for standardised methodology to aid in future data compatibility and quantitative analysis.

1. Introduction

Conventional tillage (CT) involves the disruption and mixing of soil to promote seed germination and crop establishment through beneficial soil physical interactions such as reduced water stress and mechanical impedance and to avoid crop injury from soil compaction (Nawaz et al., 2013; Finch-Savage and Bassel, 2016). In addition to lowering soil bulk density, inversion ploughing acts as a non-chemical control mechanism for weeds, incorporates crop residue into deeper soil layers and homogenises the soil seedbed for even crop growth (Blunk et al., 2018). Ploughing can also temporarily alleviate compaction stress from intensive or poorly timed traffic, although it is well established that regular tillage leads to degradation of important biophysical properties, resilience and the ecology of the soil (Lal et al., 2007). As such, CT has been implicated in reducing biomass or abundance of soil macrofauna, mesofauna, and microorganisms (Kladivko, 2001; Briones and Schmidt, 2017), in increasing susceptibility to compaction and erosion (Hamza and Anderson, 2005; Blanco-Canqui and Ruis, 2018; Klik and Rosner, 2020), and increasing greenhouse gases emissions from soil, especially CO_2 (Cooper et al., 2021a). Conversely, no– or zero-tillage (ZT) and minimum or reduced tillage are key strategies associated with Conservation Agriculture (CA) (Gonzalez-Sanchez et al., 2017). This approach involves reduced or eliminated anthropogenic perturbation using alternate methods of cultivation, often coupled with crop rotation and the retention of soil surface crop residues (Derpsch et al., 2014). The immediate effects of stopping tillage can have detrimental effects such as increased bulk density, reduced infiltration and hydraulic conductivity (USDA-NRCS, 2016; Li et al., 2020), with some collapse of soil pore structure and hydraulic function in the surface layer (Reichert et al., 2009). However, it has also been suggested that ZT can improve soil quality, farm economy and even reduce global warming potential (Mangalassery et al., 2015; González-Sánchez et al., 2016; Haddaway et al., 2017; Blanco-Canqui and Ruis, 2018; Shakoor et al., 2021; Cooper et al., 2021a) when a biologically-driven soil structure is allowed to develop over time. Furthermore, it has been shown that soils under ZT can improve beyond their initial conditions for properties such as

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available water capacity, water-stable aggregation, and hydraulic conductivity through the accumulation of organic matter and biopores (Reichert et al., 2009; Li et al., 2020). The evolution of pore structure in soils post-tillage is poorly understood; despite considerable research in recent years, it is still unclear how, and over what timeframe the adoption of ZT practices influences the development of pore structure and recovery of associated hydraulic properties when compared with CT practices.

Bulk density and soil porosity are intrinsically connected soil properties with an increase in one leading to a decline in the other. Li et al. (2020) showed bulk density significantly increased in all but sandy soils under ZT, but only within the first 6-years of ZT management with bulk density significantly lower in ZT after 12 years. This suggests the change in soil management from CT to ZT results in an initial reduction in porosity, likely due to the lack of stability of ephemeral macropores and dispersal of unstable soil fragments generated by intensive cultivation practices (Or et al., 2021). This change also initiates a new, biologically-driven development of pore structure which can recover and enhance porosity beyond the values observed in CT. Inter-aggregate pores in soil under CT are created by mechanical fragmentation and reorganisation of soil clods during cultivation and subsequently abiotic processes. Whereas under ZT, pores originate from biological processes, formed from earthworm or other faunal activity, as well as the propagation and decay of roots which are stabilised with the deposition of organic matter and microbial mucilage. However, the abundance, size, shape and stability characteristics of these pores between ZT and CT may be quite different, providing alternate soil hydraulic functionality and root interactions (Kautz, 2015; Landl et al., 2019). Mesopores and micropores are responsible for the retention of water within soil. Water in these pores becomes less mobile as pore size decreases (Kirkham, 2014), contributing less to hydraulic flow but more to hysteresis, water redistribution, and availability to plants due to high surface area and capillary effects (Luxmoore, 1981). These pores play an important role in soil reactivity, providing sites for microbiological processes and diffusive solute flow into soil aggregates (Smucker et al., 2007). However, investigation of pores at this scale typically requires assessment of a smaller sample size or specificity, and thus, there is a loss of valuable contextual information regarding soil spatial heterogeneity and pore geometry.

Soil porosity, numbers of macropores, and pore connectivity are well established as relevant and important indicators of several soil functions including those of hydraulic and biochemical origin (Jarvis, 2020; Rabot et al., 2018; Landl et al., 2019). Kay and VandenBygaart (2002) reviewed literature investigating ZT effects on porosity and pore characteristics and concluded the loss in porosity from converting to ZT is linked with changes to the pore size distribution, with macroporosity increasing as mesopores collapse. They also posited that the largest differences occur after at least 15 years, but that pore size distribution and continuity, especially of meso- and micropores, are very rarely addressed in the literature. However, since then, various techniques, some of them new, have been regularly applied to soil to reveal changes in pore structure and function after tillage, including X-ray Computed Tomography (XRCT), Mercury Intrusion Porosimetry (MIP), Electrical Resistivity Tomography (ERT) and Soil Water Retention Curves (SWRC) (Fig. 1a–d). We hypothesised that the consolidation of information provided by the application of these methods would reveal significant and coherent changes across paired ZT and CT studies. In this work we sought to collate and compare the findings from various scales across both space and time from 34 studies spanning the last 20 years between ZT and CT management. The aim was to identify key congruent ideas and points of contention between studies investigating the pore network and associated hydraulic properties, and to gain insight into the influence of time (since conversion to ZT), texture, depth and/or pore size on the pore network under ZT management.

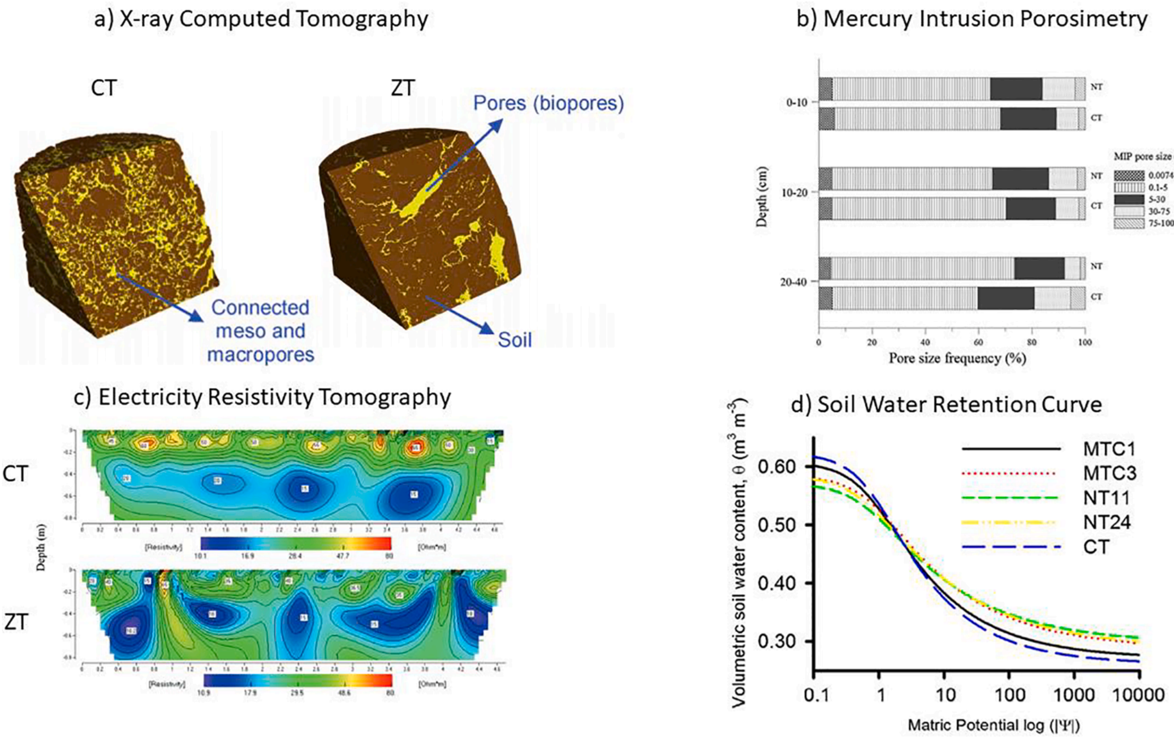

Fig. 1. Typical graphical outputs of the techniques discussed with representative comparison of soil under Zero-tillage; ZT (aka. No tillage; NT) with one under Conventional Tillage; CT, a) reconstructed cores highlighting the differences in the 3D pore network of a 36-year ZT from Pires et al. (2019), b) pore size distribution in different pore size classes in a 2-year ZT from Dal Ferro et al. (2014), c) 2D transect of a 3-year ZT from Basso et al, (2010), d) water retention curves of 11- and 24-year ZT from Tuzzin de Moraes et al. (2016).

2. Materials and methods

Relevant literature was identified using a combination of search terms in Web of Science returning over 180 results using the following search terms "*TS = (soil AND (zero-till* OR zero till* OR no-till* OR no till* OR conservation agriculture OR direct drill*) AND (conventional OR plough* OR plow*) AND (X-ray OR X ray OR tomography OR mercury intrusion OR water retention OR water characteristic OR water release OR geoelectric OR Electrical resistivity) AND (tortuosity OR connectivity OR pore structure OR pore architecture OR pore network OR pore shape OR anisotropy OR pore continuity OR porosity OR pore size OR macropore OR biopore OR pore OR burrow OR galler* OR galer*))) AND LANGUAGE: (English)*" with a timespan from 2000 to 2021. Literature was eliminated from the analysis if it did not meet the following criteria: detailed the investigated soil, reported paired findings of CT and ZT, and used at least one of the aforementioned measurement techniques. This resulted in 34 unique papers being selected from a range of soil types, locations, and periods under sustained ZT management from 0 to 36 years (Table 1.). The effects of ZT on parameters such as bulk density, physical aggregate properties, hydraulic conductivity and available water capacity have been reviewed recently by Li et al., (2019, 2020). These four measurement techniques (XRCT, MIP, WRC, ERT) were chosen to provide relevant and comparable morphometric parameters and to update our understanding on approaches that have not been assessed together more recently. Under a conventional comparison of land management, up to 10 years may not typically be considered 'short-term', however Mangalassery et al. (2015) found that 5–10 years was not long enough to resolve significant effects of zero-tillage on pore network properties. Additionally, signs of structural changes at the meso/micro scale were recorded in aggregates under ZT for 15 years (Cooper et al., 2021b), and the first signs of differences in carbon sequestration between ZT and CT recorded at around 11–15 years (Cooper et al., 2021a) which is also a good indicator of functionally significant structural changes. Also, most papers we reviewed investigated > 10-year ZT, and thus to establish a qualitative breakpoint that would provide enough data to support a reasonable comparison of period under sustained ZT management, up to 10 years was considered short term and beyond this considered long term. Many papers report their own specific pore size classes, but several report an effective diameter of 75 μm as a transition from macroporosity to meso- or microporosity, which likely relates to the pore size class definitions established by Brewer (1975). These pore size classes differ in the hydraulic functionality they provide to soil. Specifically, macropores provide rapid free drainage via gravity as the main driving force, micropores transport fluids by capillary forces and provide water retention for evapotranspiration, whereas mesopores determine the redistribution of water with some overlap between the two other classes (Luxmoore, 1981; Nimmo, 2005). Due to the commonality of Brewers system in reporting we adopted this classification system. However, due to similarities in hydraulic function and the limited number of studies investigating differences between meso- and microporosity, we chose to combine these two pore size classes in discussion.

A quantitative approach to the analysis of the available data was undertaken, however, unfortunately the data were not extensive enough ranging across the selected factors of interest to generate a robust and appropriate statistical analysis and thus were excluded from this study.

3. Results and discussion

3.1. Macroporosity under short-term (< 10 years) ZT

3.1.1. X-ray computed tomography (XRCT)

XRCT is a non-destructive imaging technique which allows the differentiation of materials based on their X-ray attenuation properties (Withers et al., 2021). This approach provides three-dimensional (3-D) information from soil regarding its porous architecture (Taina et al., 2008). The influence of the pore network on hydraulic dynamics can then be assessed using comparative approaches (Helliwell et al., 2013) such as water retention, infiltration and air permeability (Naveed et al., 2017), or transport modelling approaches such as with HYDRUS (Šimůnek, et al., 2012) or CXTFIT (Soto-Gómez et al., 2018, 2020). XRCT can image a wide range of pore sizes, from macropores (>75 μm) through to mesopores (30–75 μm) and some micropores (<30 μm) at fine-scale resolution depending on the dimensions of the sample.

Mangalassery et al. (2015) found that macroporosity, pore size and pore surface area were reduced at the surface (0–10 cm) of 5–10-year ZT soils when compared with CT, but with diminished effect at the subsurface (10–20 cm). Other short-term studies (<10 years) using XRCT to examine ZT and CT soil have also shown lower macroporosity at the surface under ZT, but no clear pattern associated with soil depth. For example, while three studies independently identified decreased macroporosity in the surface layer (0–10 cm) of their respective silt loam, sandy loam and clay loam ZT soils (Gantzer and Anderson, 2002; Dal Ferro et al., 2014; Li et al., 2021), at the subsurface (10–20 cm), Dal Ferro et al. (2014) identified increased macroporosity in a sandy loam. Pöhlitz et al. (2018) also identified a reduction in pore space in a silt loam and Piccoli et al. (2017) identified a slight reduction in macroporosity in the 0–50 cm layer across four ZT sites ranging from silty clay loam to loam. Studies have also used XRCT to examine macroporosity within isolated aggregates but found negligible differences at this scale (Garbout et al., 2013; Malobane et al., 2019). Pöhlitz et al. (2018) specifically investigated the effect of increased mechanical loading on ZT and CT soils and found that increased loading up to 50 kPa resulted in very little differences on ZT pore structure, whereas CT soil quickly lost its macroporosity and pore connectivity with bulk density increasing rapidly. Despite contrasting responses of ZT on macroporosity, many studies have consistently reported a higher pore connectivity under ZT (1 year, Dal Ferro et al., 2014; 3 years, Piccoli et al., 2017; 5 years, Li et al., 2021), which is suggestive of biologically mediated pore development and persistence. Theoretically, the lack of anthropogenic disturbance facilitates the development of a well-connected pore network via complex biological processes and abiotic cycles. But despite significant changes in macroporosity, ZT may not induce significant responses in soil functional properties, for instance Johnson-Maynard et al., (2007) found earthworm populations were significantly increased in ZT soils after 3 years but no differences in bulk density and saturated hydraulic conductivity (Ksat) over the same period.

3.1.2. Soil water release characteristic (SWRC)

SRWCs provide information about the fate of water in soil at a given moisture condition. Given that increasingly smaller pore sizes retain more at increasingly negative pressures, soil water as a function of pressure allows an approximation of the pore size distribution within a soil sample (Nimmo, 2005). This method is well established due to relatively low cost of the equipment and increased accessibility in comparison to XRCT. Using SWRC, three previous studies identified no significant differences between ZT and CT in their respective work on a freshly converted ZT silt loam, a 2-year ZT on loam soil and 3-year ZT on a compacted clay soil (Xu and Mermoud, 2001; Abu and Abubakar, 2013; Brunel-Saldias et al., 2016). However, repeated wetting and drying cycles, which are involved in obtaining data with this method, have been shown to initiate different responses on the respective pore structures within tilled and zero-tilled soil, raising questions regarding the reliability of this method for investigating contrasting tillage practices (Müller et al., 2019; Pires et al., 2020; de Oliveira et al., 2021). Additionally, Cheik et al. (2021) showed biopores in a clay soil remain stable under wetting and drying cycles, whereas cracks in clay were less stable and generated large and increasing variability under higher and repeated flow conditions.

3.1.3. Electricity resistivity Tomography (ERT)

Geoelectrical methods allow the monitoring of real-time processes and resolution of soil heterogeneity over a large spatial scale with

Table 1
List of reviewed literature and the main porosimetry techniques: Electrical Resistivity Tomography (ERT); Mercury Intrusion Porosimetry (MIP); Soil Water Retention Curve (SWRC); X-ray Computed Tomography (XRCT) – Pore size classes: Total porosity (φ); Macroporosity (M); mesoporosity (m); microporosity (μ) – and descriptors: Pore size distribution (PSD); No significant difference (NSD).

Source	Technique	Soil texture	Depth range (cm)	Short or Long-term	Years under Zero-tillage	Resolution or Pressure head |Ψ|	Country	Pore size class	Zero-tillage effect on pore characteristics
Basso et al., 2010	ERT	Sandy clay loam	0–80/200	Short	3	none	Italy	N/a	Lower resistivity in upper 30 cm, values below 30 cm were not different
Dal Ferro et al., 2014	XRCT	Sandy loam	0–40	Short	2	54–2250 μm	Italy	M	Lower M in 0–10 cm but increased connectivity, higher in 10–30 cm, alternate PSD at 0–10 and 20–40 cm
Pöhlitz et al., 2018	XRCT	Silt Loam	12–18	Short	3	60 μm	Germany	M	Lower M, lower connectivity, higher mean macropore diameter
Li et al., 2021	XRCT	Clay loam	0–10	Short	3	55 μm	China	M	Lower M with alternate PSD, lower critical pore diameter, higher specific surface area, connection probability and anisotropy
Piccoli et al., 2017	XRCT	Silty clay loam over loam	0–50	Short	5	26 μm	Italy	M/m	NSD in φ, PSD, or morphometric parameters
Malobane et al., 2019	XRCT	Sandy clay loam	0–10	Short	5	18.9 μm	South Africa	M/m	Aggregates: NSD in φ but alternate PSD
Garbout et al., 2013	XRCT	Unclear	10–20	Short	6	800 μm	Denmark	M	Aggregates: NSD in φ or morphometric parameters
Gantzer and Anderson, 2002	XRCT	Silt loam	2.5–10	Short	6	150 and 1000 μm	Mexico	M	Lower M, lower pore perimeter and fractal dimension, higher circularity
Mangalassery et al., 2015	XRCT	Various	0–20	Short	5 to 10	64 μm	UK	M	Lower M, lower pore surface area, larger effect at surface (0–10 cm) than subsurface (10–20 cm)
Xu and Mermoud, 2001	SWRC	Silt loam	10, 30	Short	>1	0.6–150 m	China	M/m/μ	NSD at 10 cm or 20 cm in M or μ
Abu and Abubakar, 2013	SWRC	Loam	0–30	Short	2	0.075–1500 kPa	Nigeria	M/m/μ	NSD in M, lower m and μ at 0–5 cm, higher in 5–15 cm and 15–30 cm
Brunel-Saldias et al., 2016	SWRC	Sandy loam over clay	0–60	Short	3	0.2–1500 kPa	Chile	M/m/μ	NSD in φ or PSD
Fernández-Ugalde et al., 2009	SWRC	Silt loam	0–30	Short	7	33–1500 kPa	Spain	m/μ	Lower m (>9 μm), higher μ (<9 μm), larger effect at 0–5 cm than 5–15 cm or 15–30 cm
Dal Ferro et al., 2014	MIP	Sandy loam	0–40	Short	2	0.0074–100 μm	Italy	m/μ	NSD in T, PSD, or network connectivity
Piccoli et al., 2017	MIP	Silty clay loam over loam	0–50	Short	5	0.0074–100 μm	Italy	m/μ	Lower m, higher μ (within ultramicro subfraction 0.1–5 μm)
Cooper et al., 2021a	XRCT	Various	0–30	Other	1 to 15	50 μm	UK	M	Lower φ for 1–5 y, 6–10 y and 11–15 y. φ and surface connected porosity higher in 6–10 y and higher still for 11–15 y than 1–5 y
Lucas et al., 2019b	XRCT	Silty clay loam	0–60	Other	1 to 24	10 μm	Germany	M/m	Not strictly ZT vs CT, but valuable as a structural chronosequence
Cooper et al., 2021b	XRCT	Clay	0–20	Other	2, 15, 31	50 and 1.5 μm	Brazil	M/m/μ	Lower φ for 2y, NSD in T for 15 y, higher T for 31 y at 50 μm (core scale). Aggregates: lower φ for 2y, further decreases in φ for 15 y and 30y respectively at 1.5 μm, alternate PSD for 15 y and 31 y
Müller et al., 2009	ERT	Silt loam	0–300	Long	15	none	Germany	N/a	Lower resistivity through depth profile (0–300 cm), higher resistivity along surface profile (0 cm)
Müller et al., 2019	XRCT	Silt loam	0–5	Long	14	33 μm	New Zealand	M/m	NSD in φ, smaller mean pore diameter with alternate PSD
Li et al., 2021	XRCT	Sandy loam	0–10	Long	15	55 μm	China	M	Higher M with alternate PSD, lower critical pore diameter, higher specific surface area and anisotropy, NSD in connection probability
Guo et al., 2020	XRCT	Clay loam	0–5	Long	15	25 μm	China	M/m	Lower φ with alternate PSD, higher connectivity, lower anisotropy and fractal dimension
Guo et al., 2021	XRCT	Clay loam	0–15	Long	15	100 μm	China	M	No pre-treatment data, higher connectivity, lower volume fraction and anisotropy in all treatments, varying effects of treatments on PSD
Kravchenko et al., 2011	XRCT	Loam	0–20	Long	20	14.6 μm	USA	M/m	NSD in φ, lower m

(*continued on next page*)

Table 1 (*continued*)

Source	Technique	Soil texture	Depth range (cm)	Short or Long-term	Years under Zero-tillage	Resolution or Pressure head |Ψ|	Country	Pore size class	Zero-tillage effect on pore characteristics
Schlüter et al., 2020	XRCT	Silt loam	10–20	Long	26	60 μm	Germany	M	Lower M, lower connection probability (Γ), higher average pore diameter and critical pore diameter
Munkholm et al., 2016	XRCT	Loam	10–20	Long	30	40 μm	Canada	M/m	Lower φ, Aggregates: NSD in φ
Galdos et al., 2019	XRCT	Clay	0–12	Long	30	70 μm	Brazil	M	Higher M, lower Euler characteristic and tortuosity values, alternate pore shape distribution
Borges et al., 2019	XRCT	Clay	5–15	Long	30	60 μm	Brazil	M	Lower M, lower Euler characteristic at 5–10 cm, higher Euler characteristic at 10–15 cm, alternate PSD and pore shape distribution
de Oliveira et al., 2021	XRCT	Clay	0–10	Long	35	35 μm	Brazil	M/m	Lower M, lower m, lower accessed porosity, alternate PSD
Pires et al., 2019	XRCT	Clay	0–10	Long	36	35 μm	Brazil	M/m	Lower φ, lower M, higher μ, higher volumetric Euler characteristic and Euler number of largest pore, lower tortuosity of Z dimension, alternate PSD, NSD in pore shape distribution
Tuzzin de Moraes et al., 2016	SWRC	Clay	0–30	Long	11	3–1500 kPa	Brazil	M/m/μ	Lower M and higher μ at 0–10 cm, NSD at 10–20 cm, higher M and lower μ at 20–30 cm, alternate PSD at 0–10 cm and 20–30 cm
Imhoff et al., 2010	SWRC	Silty clay loam	0–5	Long	13	0–1500 kPa	Argentina	M/m/μ	NSD in T, higher number of hydraulically effective pores per unit area
Soracco et al., 2018	SWRC	Loam	0–10	Long	14	0–150 *m*	Argentina	M	Lower M
Gao et al., 2019	SWRC	Sandy loam	0–20	Long	16	0.1–150 *m*	China	M/m	Higher M at 0–10 cm which was diminished at 10–20 cm, lower m
Lipiec et al., 2006	SWRC	Silt loam	0–20	Long	18	0.1–100 *m*	Poland	M/m/μ	Lower M, lower m, higher μ, much diminished effect at depth (10–20 cm)
Tuzzin de Moraes et al., 2016	SWRC	Clay	0–30	Long	24	3–1500 kPa	Brazil	M/μ	Lower M and higher μ at 0–10 cm, NSD at 10–20 cm, higher M at 20–30 cm, alternate PSD at 0–10 cm and 20–30 cm
Borges et al., 2019	SWRC	Clay	0–10	Long	30	1–800 kPa	Brazil	M/m/μ	Lower M, higher m and μ
Churchman et al., 2010	MIP	Sandy clay/sandy clay loam	2–5	Long	18	0.03–100 μm	Australia	m/μ	Lower m, higher μ
Wairiu and Lal, 2006	MIP	Silt loam	0–20	Long	35	0.005–500 μm	USA	M/m/μ	NSD in M, m or μ at 0–10 cm or 10–20 cm, higher median pore radius in one of two sites

minimal soil disturbance (e.g. Cimpoiaşu et al., 2020). For example, ERT presents a way to investigate soil hydraulic dynamics, which can provide insights into pore networks. For instance, a particularly well-connected pore network might allow conductive regions within the soil profile, whereas a compacted layer with limited connected pores would not allow the conduction of water and thus increase resistivity. However, resistivity also correlates with many other edaphic properties such as the presence of root systems, mineral surface conductivity, water content, porosity and pore architecture (Abidin et al., 2014; Cimpoiaşu et al., 2020) somewhat constraining interpretation. Basso et al. (2010) investigated the spatial variation between treatments of CT and a 3-year ZT sandy clay loam, finding significantly lower resistivity in the 3-year ZT soil, though differences were only apparent in the upper layers and diminished with increasing soil depth beyond 30 cm. Automatic resistivity profiling reflected these observations, showing significantly lower resistivity in the 0–50 cm layer of ZT than of CT (Basso et al., 2010). The higher resistivity values identified in tilled soil layers indicated that soil water electrical conductivity is decreased, due to an increased number and size of free draining macropores (Basso et al., 2010).

3.2. *Macroporosity under long-term (>10 years) ZT*

3.2.1. *X-ray Computed Tomography (XRCT)*

With an extended period under continuous ZT management, here defined as > 10 years, roots can be expected to prefer growth through existing channels known as biopores (Or et al., 2021; Zhou et al., 2021). This can stabilise or disperse the surrounding soil material depending on the composition of root exudates and microbial mucilage (Czarnes et al., 2000; Naveed et al., 2017). Also, propagating roots in poorly structured soils can generate micro-compaction sites (Lucas et al., 2019a), stabilising newly developed biopores. As such, in a chronosequence study over 24 years, biopores established within the first 3 years of management persisted within the untilled layer (40–60 cm) resulting in a highly branched network, whereas biopores in the tilled layer (0–20 cm) originated from new root proliferation and fragmentation of older biopores (Lucas et al., 2019b) (Fig. 2). Elsewhere, pre-existing macropore networks at depth, and particularly true of biopores, have been shown to strongly promote deep rooting behaviour of wheat regardless of genotype (Zhou et al., 2021). Additionally, Gao et al. (2019) showed that long connected macropores were more commonly observed in soil under 16 years ZT than CT. In long-term ZT, a layer of compacted soil may develop at c. 7–20 cm, and the plough pan may remain intact (Reichert et al., 2009). Thus, it may be important that crops are selected based around rooting strategy when adopting ZT to promote the establishment of a persistent and connected macro(bio)pore network throughout deep layers. Concerning intra-aggregate pores, Kravchenko et al. (2011) found few differences between aggregates of 20 years ZT and CT, but identified fewer small pores (15–60 μm) in the outer portions of ZT aggregates studied. Munkholm et al. (2016) found no discernible effects on any investigated pore properties under 30 years ZT. This suggests, along with the lack of effects observed in short-term intra-aggregate studies, that ZT practices may mainly impact on macroporosity in the bulk soil, though additional long-term studies on ZT aggregate porosity would prove valuable.

Other long-term studies (>10 years) using XRCT have observed

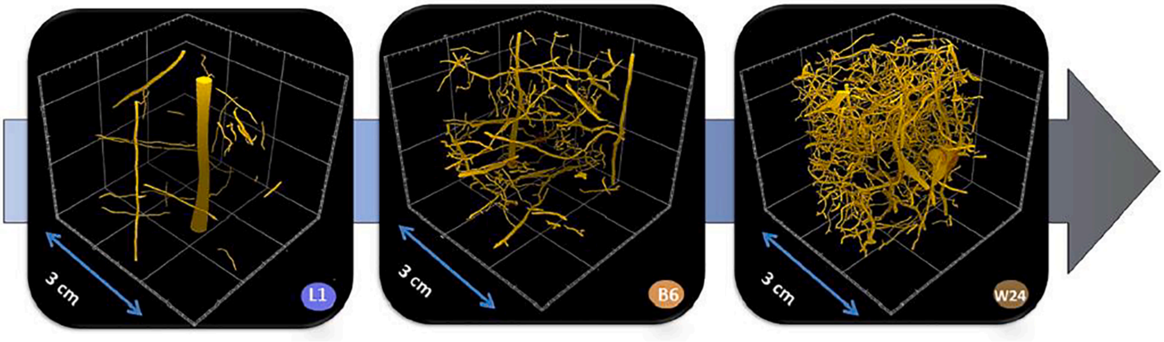

Fig. 2. Biopores in undisturbed soil from 1, 6 and 24 years at 50 cm depth, pores characteristic from root structures established in the first few years are still observable after 24 years (Lucas et al., 2019b).

differences in pore network characteristics between ZT and CT, but also differences in their respective relationships with other treatments, such as irrigation, residue application, and addition of earthworms. For instance, Guo et al. (2021) showed in a clay loam ZT treatments with earthworms had a higher pore volume and number of macropores (>500 μm) at the expense of smaller macropores (100–500 μm), and additionally a higher anisotropy and smaller connectivity than treatments without earthworms, though the study provided no pre-treatment data, ultimately constraining interpretations. Elsewhere, earthworms have demonstrated the ability to bring both loose and compacted soil material to a similar effective mechanical state through ingestion and casting spanning a few decades (Barré et al., 2009). Earthworms also generate alternate bioturbation patterns between contrasting tillage systems (Piron et al., 2017), and an alternate stratification of organic material in ZT topsoil can promote endogeic activity (Capowiez et al., 2021). Long-term irrigation can also have contrasting implications for the pore properties of each tillage treatment, as Müller et al. (2019) showed irrigation had distinct and contrasting effects on pore connectivity, pore size distribution, and mean pore diameter between ZT and CT. This evidences a dynamic relationship between soil water and the soil pore network, as identified by Pires et al. (2020), who observed significant changes to pore structure from repeated wetting and drying cycles as part of measurement of the SWRC on a ZT clay soil. de Oliveira et al. (2021) reported significantly increased connected porosity and increases in pore sizes across the entire pore size distribution when 35-year ZT clay soil was subject to wetting and drying cycles, whereas CT exhibited the inverse effect. The pore generation identified under ZT was explained by the swelling of clays forming cracks during shrinking processes, and the pore degeneration in CT explained by aggregate disintegration and subsequent coalescence (Ghezzehei and Or, 2000).

Several studies have observed a significantly lower macroporosity in surface layers (0–20 cm) of fine-textured long-term ZT soils (Borges et al., 2019; Pires et al., 2019; Guo et al., 2020; Schlüter et al., 2020), and two of the studies we assessed reported higher macroporosity (Galdos et al., 2019; Cooper et al., 2021b). Likewise, a study of 80 paired ZT and CT sites of various management lengths (1–15 years) found macroporosity was decreased when compared with CT (Cooper et al., 2021a). However, porosity and surface connected porosity increased with time under ZT. Additionally, surface connected porosity dominated the total porosity of 11–15-year ZT but only represented a small proportion of CT total porosity suggesting a potential hydraulic advantage to long term ZT. In studies that included unmanaged secondary forest soil in their investigation, the forest soil more closely resembled ZT soil layers than those of soil under CT (Borges et al., 2019; Pires et al., 2019), suggesting that ZT management initiates a transformation towards the biologically generated pore structure observed in undisturbed/native soil systems. Soils under ZT have showed an increased abundance of anecic earthworms (Schlüter et al., 2020). With an increase of biologically driven pore formation by plant roots and edaphic fauna, a tendency towards observing a higher relative frequency of pores with an elongated shape could be expected. As such, a slightly increased relative number of pores and porosity in those of elongated shape were identified (Borges et al., 2019; Galdos et al., 2019). Undoubtedly, with biological activity and wetting/drying cycles inflicting distinct changes between ZT and CT, errors resulting from sampling snapshots of what is clearly a highly dynamic process are likely to occur (Almquist, 2020). While there is some evidence to suggest temporal variation in hydraulic properties of ZT and CT soil (Xu and Mermoud, 2001; Schwen et al., 2011; Kreiselmeier et al., 2019), there is currently little evidence on temporal variation, or variation with the patterns of rainfall on X-ray-resolvable porosity and pore network characteristics between these two practices.

Li et al., (2021) identified higher water repellency along with their investigations of pores using XRCT at both short- and long-term ZT sites when compared against CT. They identified a greater ethanol sorptivity due to an improved connectivity in the ZT pore network, but a reduced water sorptivity due to an increase in hydrophobic substances. An alternate stratification of soil organic matter has been identified within ZT, increasing at the surface as a result of increased residue retention (Kay and VandenBygaart, 2002; Haddaway et al., 2017; Camarotto et al., 2020). With the additional elimination of soil disturbance, the composition and organisation of organic matter throughout the soil profile can be expected to change, resulting in coatings on the surfaces of biopores (Leue et al., 2013; Haas et al., 2018). These coatings can generate a slower wettability of aggregates by increasing water repellency in ZT, preventing slaking and maintaining higher aggregate stability (Blanco-Canqui, 2011; Behrends Kraemer et al., 2019), which is another physical property identified in ZT soils increasing over time (Li et al., 2020) and one that is important for soil hydraulic performance.

3.2.2. *Electricity resistivity Tomography (ERT)*

Using various geoelectrical methods, Müller et al. (2009) identified increased water holding capacity in a 15-year ZT silt loam compared with CT. They observed greater heterogeneity in soil structure and lower water retention in the upper layer (0–50 cm) of CT soil, which was explained by tillage induced aggregate slaking and particle settling into a more homogenous geoelectrical profile in the deeper layer (50–150 cm). Where differences in geoelectrical profiles were identified, it would be particularly useful in future research to follow-up with an imaging technique to more accurately explain such variation both within and between tillage treatments (Cimpoiaşu et al., 2020).

3.2.3. *Soil water retention curves (SWRC)*

The studies we assessed which used SWRC to describe macroporosity and associated hydraulic properties for CT and ZT soils showed conflicting results. Two studies on a silt clay loam and a sandy loam soil respectively under long-term ZT management showed increased macroporosity at the soil surface (Imhoff et al., 2010; Gao et al., 2019). Imhoff et al. (2010) additionally found rotation with graminaceous species induces a greater structural quality in ZT systems. Lipiec et al. (2006) identified a smaller macroporosity, infiltration rate and stained porosity at the surface of a silt loam, but diminished differences between ZT and CT at 10–20 cm depth, suggesting CT practices mainly induce an increased frequency of macropores restricted to the immediate upper soil layer. This is supported by Lin (2011) who found changes in deeper soil layers are progressively reduced by their limited exposure to and interactions with surface processes. However, Tuzzin de Moraes et al. (2016) recorded significantly reduced macroporosity in the surface layer of ZT clay when compared with CT, but increased macroporosity at depth (20–30 cm). Despite the reduced surface macroporosity, the 11-year ZT soil showed an increased infiltration rate and K_{sat} than CT, which significantly increased after 24-years. Whereas Imhoff et al. (2010) found increased macroporosity alongside increased hydraulic conductivity in a ZT silt loam and Borges et al. (2019) observed decreased macroporosity and decreased K_{sat} in a clay soil. This reinforces that quantification of macroporosity alone is insufficient to estimate the effects on fluid transport, and that consideration is needed of a more complex interaction with soil texture, soil depth and the assessment of the 3D pore network, such as pore continuity, tortuosity, and orientation, which could be addressed by dynamic modelling processes and percolation theory (Hunt and Sahimi, 2017). For example, Soto-Gómez et al. (2020) applied percolation theory to imaged soil cores under different soil management practices to extract the percolation backbone, i.e. the part of the pore network most responsible for hydraulic flow. They found significant differences in properties of the backbone between shallow tilled soil and ZT, such as pore volume and surface area, as well as pore circularity/roundness and fractal dimension, and found significant correlations of said properties with dispersion of particulate and solute tracers. However, due to technical limitations, this investigation only resolved macropores > 1.2 mm in effective diameter, and thus was unable to observe other hydraulically relevant pores below this size. Finally, Soracco et al. (2018) identified temporal variation in soil physical quality indicators in the 0–10 cm layer but found no evidence to suggest seasonal variation effected ZT and CT soil differently.

3.3. Meso- and microporosity under short-term (< 10 years) ZT

3.3.1. Mercury Intrusion Porosimetry (MIP)

MIP involves the progressive application of highly specific pressures on liquid mercury, overwhelming its high surface tension and forcing it into pores without wetting the media (Simms and Yanful, 2004). This prevents clay swelling in soils and the associated inaccuracies during pore size quantification. The method can provide information about soil porosity at both the micro and meso scales, classifying pores ranging from 0.0074 to 100 μm in diameter. One important aspect and fallback is the ability of mercury to penetrate only through accessible and connected porosity, potentially leading to indeterminate mischaracterisation of larger pores connected by smaller pores (Zhang et al., 2019).

In their study of 1–2 years ZT, Dal Ferro et al., (2014) identified no significant differences in MIP parameters on a sandy loam, including total porosity and connectivity, between tillage treatments in surface and subsurface layers. However, in contrary to CT, layers of ZT showed slight increases in structural complexity with depth, and though not significant, there was a slightly larger proportion of ultramicropores (0.1–5 μm) and smaller proportion of mesopores identified in ZT in the 20–40 cm layer (Dal Ferro et al., 2014). This difference was significant in another study considering 4 sites with silty clay loam under 5 years continuous management, where ZT showed a larger ultramicroporosity and smaller mesoporosity compared with a soil under CT (Piccoli et al., 2017). But there were no interactions between management practice and soil layer investigated, indicating a treatment-independent increased porosity at the surface. This was contradicted by Malobane et al. (2019) who, using XRCT at 18.9 μm, found mesoporosity in ZT increased above that in CT in on a 5-year sandy clay loam, though this study only investigated aggregates collected from the surface layer (0–10 cm) and quantified pores of a size very close to their scanning resolution. However, MIP and XRCT have previously been shown to contradict when directly compared due to non-uniform pore geometry and connectivity in heterogenous complex media resulting in the mischaracterisation of larger pores in MIP (Dal Ferro et al., 2012; Wang et al., 2020; Xue et al., 2020), and in pixel edge effects of pores close to the XRCT scanning resolution resulting in the mis-characterisation of image 'noise' as small pores.

3.3.2. Soil water retention curves (SWRC)

Three studies from our *meta*-analysis which used SWRC identified a reduction in ZT mesoporosity at the surface of differently textured soils, including sandy loam, silt loam and loam, and also identified either an increase (Abu and Abubakar, 2013) or smaller reduction (Fernández-Ugalde et al., 2009; Brunel-Saldias et al., 2016) in mesoporosity at depth. Fernández-Ugalde et al. (2009) identified a higher relative frequency of micropores in their silt loam ZT soil throughout 0–30 cm depth which had a significant positive impact on total available water content, whereas in the loam soil studied by Abu and Abubakar (2013) microporosity was increased in ZT only in the 15–30 cm layer. Brunel-Saldias et al. (2016) found no significant difference between treatments and went on to describe ZT with subsoiling, a practice to alleviate compacted layers at depth, as the most beneficial treatment for managing this soil, with significantly increased rooting density throughout the soil profile (0–80 cm).

3.4. Meso- and microporosity under long-term (>10 years) ZT

3.4.1. X-ray Computed Tomography and mercury Intrusion Porosimetry

Lucas et al. (2019b) used a hierarchical subsampling strategy to investigate differences between ZT and CT soils and found the enhanced pore connectivity observed in ZT soil horizons was only at the finer scales. Likewise, Cooper et al. (2021b) found that the smallest pore size classes investigated (3–9 μm) comprised the largest proportion of pores in 15 and 31-year ZT aggregates. This suggests that additional significant differences in structural complexity between CT and ZT soil may only be resolved when investigated at smaller scales. However, these differences have not been supported to date when using MIP, as Churchman et al. (2010) found no difference in pore size distribution between CT and ZT practices after 18 years. Wairiu and Lal (2006) also reported no significant differences of aggregate porosity between CT and ZT at two long-term sites (35 years) with silt loam soils even though there were slight differences namely an increased volume of meso- and micropores in ZT at depth (10–20 cm). These investigations suggest, through their studies of paired long-term sites, that the pore structure generated by biological perturbation cannot be separated from that of intensive tillage using MIP.

3.4.2. Soil water retention curves (SWRC)

Using water retention curves, Lipiec et al. (2006) observed a higher bimodal frequency of micro and mesopores within the upper layer (0–10 cm) of a ZT silt loam. This was reinforced by Tuzzin de Moraes et al. (2016) who investigated an 11-year and 24-year ZT clay soil and observed increased volume fractions of all pores identified in a 24-year ZT compared to an 11-year ZT and a CT soil, suggesting the pore network continues to develop over time as biopores are generated, stabilised and remain extant. Water retention increased in a long-term (>30 years) ZT clay soil explained by a greater volume fraction of meso and micropores < 75 μm (Borges et al., 2019). However, two studies found slight reductions in mesoporosity in a ZT sandy loam (Gao et al., 2019), and micro- and mesoporosity in a ZT silt clay loam (Imhoff et al., 2010). And while Gao et al. (2019) found no significant effects of this reduced mesoporosity in ZT on any investigated soil water properties, including field capacity, wilting point, and available water, Imhoff et al. (2010) found significantly increased K_{sat} in ZT at tension values of

0, 1.5 and 3 cm.

3.5. Implications of ZT for agrochemical transport

With tillage, depth and soil texture creating changes in the soil pore network, it was expected that previous work would have detected and quantified significant changes in agrochemical and solute transport between ZT and CT managed soils. Indeed, a small number of reviews have assessed pesticide fate, runoff, and transport between conventional and conservation agricultural practices (Flury, 1996; Holland, 2004; Alletto et al., 2010; Elias et al., 2018) and others have explored the link between soil pore properties and solute transport (Jarvis, 2020; Koestel et al., 2012). Jarvis (2020) commented that aggregate skins and linings on macropore walls generated from enhanced biological activity can reduce diffusion of solutes into bulk soil due to a reduction in the effective diffusion coefficient of anionic tracers (Köhne et al., 2002). They also posit that vertically aligned and continuous biopores, such as those generated by burrowing species and decaying roots, can have profound impacts on increasing ponded infiltration and pesticide leaching risks. Thus, in the absence of a tillage-induced redistribution and fragmentation of pores in ZT, the interactions of a pore network generated by biological processes would be expected to significantly alter the hydraulic, solute, and particulate flow dynamics though soil. As such, Alletto et al. (2010) found pesticide interception and retention was increased in conservation approaches by soil surface extant crop residues and enhanced soil organic matter, which also reduced the microbial community dependency on pesticides as a carbon source. And while the application of pesticides with a high organic matter affinity may exhibit reduced losses in runoff from improved soil stability and reduced risks of particulate erosion in ZT, well connected macropore networks maintain or increase risks to losses via leaching. Following this, recent studies have reported the increased loss of the herbicides pendimethalin and atrazine in ZT compared with CT in 13 and 11-year sites (Babal et al., 2021; Baffaut et al., 2020), while the vertical transfer of nicosulfuron, mesotrione and metaldehyde were also increased in 11 and 18-year sites using conservation approaches including ZT (Cueff et al., 2020). Elias et al. (2018) examined pesticides reported in 34 studies and found that the physicochemical properties of the pesticide controlled their concentration and load in ZT soil surface runoff, increasing with higher water solubility and lower organic solubility, whereas less mobile compounds showed no differences between tillage practices. As pesticide polarity and interactions may change at a given pH, Elias et al. (2018) also showed differences in load and concentration in runoff due to soil type and acidity, explaining that the high surface area of clay particles within soil provide increased sites for pesticide sorption, though differences between ZT and CT were better explained by the intrinsic pesticide properties. Jarvis (2020) found an increased leaching risk of relatively mobile pesticides under ZT. They hypothesised that the transport of strongly sorbing pesticides are more likely to be leached during macropore flow in soils with low aggregate stability, like those seen in CT (Li et al., 2019), when loose, mobile soil particulate matter is generated by dispersion and carried through the soil profile by moving water. Though Levanon et al. (1994) show reduced losses via leaching of atrazine, carbofuran, diazinon and metachlor from the upper 5 cm of ZT soil, which were in part explained by enhanced pesticide mineralisation rates due to increased microbial activity. Souza et al. (2015) also showed that the ZT soil microbial community could have an improved capacity for pesticide degradation due to increased frequency of genomic sequences for the metabolism of aromatics. The comparison of pesticide transport of less mobile compounds through ZT and CT via leaching has rarely been reported in the literature likely due to the greatest tillage effect being observed on pesticides with high solubility and low sorption coefficients (Elliott et al., 2000; Elias et al., 2018). Soto-Gómez et al. (2018) used colloid and solute tracers alongside XRCT to link pore geometry with transport parameters; they showed macropore roughness correlated with solute dispersion and travel time, and that pore wall linings produced by earthworms reduced solute mass transfer from mobile to immobile regions. Additionally, in pores with wall linings, the pore water velocity was increased and variability decreased, increasing preferential transport (Soto-Gómez et al., 2018). Koestel et al. (2012) identified no clear effect of land use on their *meta*-analysis of 733 breakthrough curves, and instead showed that longitudinal dispersivity increased only with the travel distance of tracers, and preferential solute transport was instead dependent on soil texture, increasing in finer textured soils. However, ZT only accounted for 31, and CT for 219 of the total number of curves analysed, thus the difference in solute transport between these specific practices may not have been fully resolved.

4. Summary

Soils are inherently complex, dynamic and highly varied which makes finding trends in the biophysical properties of soil systems such as those exposed to contrasting management systems particularly important but also very challenging. Our review reveals soil macroporosity generally decreases in ZT soils, particularly at the surface layer, but also that this change is soil texture and depth dependent, and in many cases time dependent. Despite the reductions in macroporosity, increased pore network connectivity was commonly identified in studies using XRCT to visualise undisturbed ZT soil in both short and long-term studies, indicating a swift (i.e., within the first 3 years) development of soil structural complexity. This decrease in macroporosity and increase in pore connectivity may improve water retention, trading off rapid infiltration for increased diffusivity; however, the effects on hydraulic transport and retention remain unclear and often contradictory. This is likely due to the appearance and resilience of biopores accumulating over time and at depth, and with an increased soil organic matter and reduced disturbance promoting the stabilising action of microbial communities. Studies of aggregates revealed higher stability and wettability of ZT aggregates, likely due to the reduced pore network accessibility influencing the rapidity of hydraulic flow, and of alternate physicochemical properties of pore walls, indicating that significant structural and functional changes occur within aggregates, as well as between them. This link between evolving pore structure and function is important as several studies have reported more rapid leaching of pesticides under long term ZT which may be due to the physiochemical conditions of the soil pore interface. This is also important as the global move towards conservation/regenerative agricultural systems suggests ZT is likely to increase in popularity in the future. However, many of the studies we examined limited their investigations to the upper layers of soil (0–20 cm), and less than half considered more than one of the major pore size classes with many using an arbitrary or original classification system typically depending on resolution. This, along with a lack of standardised methodology and variation in the technical equipment available to researchers, ultimately constrains data compatibility thus we urge researchers to use established pore size classes from the literature to aid future comparative work. Unfortunately, due to the constraints above, our attempts to perform a meaningful quantitative analysis were not possible due to a lack of statistical robustness, but with adoption of a more uniform appraisal system this may be possible in the future.

The soil pore network structure, and particularly the arrangement of macropores that are characteristic of biological activity (i.e., long, cylindrical, non-tortuous, surface-connected macropores), induce changes in functionality, specifically with regards to the transport of water, solutes and mobile particulate matter to deeper layers. Many studies report increased pesticide leaching under ZT, likely resulting from a combination of the contrasting origins of pore establishment (i.e., biotic and abiotic in ZT vs anthropogenic in CT), and the physicochemical properties of pore wall linings. Yet, there exists much scope for additional research in this area, specifically to explain differences in agrochemical transport and performance between ZT and CT. There is extensive evidence using multiple contrasting techniques to suggest that biologically and anthropogenically generated pore network structures differ significantly from one another. However, many studies also find the contrary i.e., that no clear differences exist between the soil pore network properties of ZT and CT. Whether this observation occurs as a consequence of taking a snapshot of a dynamic and initially degenerative process, or that additional and hidden factors are at play in soil structure formation and regulation, remains to be elucidated. There exists considerable potential then, to explore the sequential development of a biologically mediated pore network structure under ZT to clarify the link between soil structure evolution and changes in functionality.

Declaration of Competing Interest

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References

Abidin, M.H.Z., Saad, R., Ahmad, F., Wijeyesekera, D.C., Baharuddin, M.F.T., 2014. Correlation analysis between field electrical resistivity value (ERV) and Basic Geotechnical Properties (BGP). Soil Mech. Found. Eng. 51 (3), 117–125.

Abu, S.T., Abubakar, I.U., 2013. (2013) 'Evaluating the effects of tillage techniques on soil hydro-physical properties in Guinea Savanna of Nigeria'. Soil Tillage Res. 126, 159–168.

Alletto, L., Coquet, Y., Benoit, P., Heddadj, D., Barriuso, E., 2010. Tillage management effects on pesticide fate in soils. A review. Agron. Sustain. Dev. 30 (2), 367–400.

Almquist, V.W., 2020. Integrating complex soil dynamics using the non-equilibrium effective temperature. Front. Earth Sci. 8, 1.

Babal, B., Phogat, V.K., Sharma, M.K., Ahlawat, S., 2021. Impact of long-term conservation agriculture induced changes in soil properties on persistence of pendimethalin under different cropping systems. Soil Res. 59 (3), 299.

Baffaut, C., Ghidey, F., Lerch, R.N., Veum, K.S., Sadler, E.J., Sudduth, K.A., Kitchen, N.R., 2020. Effects of combined conservation practices on soil and water quality in the Central Mississippi River Basin. J. Soil Water Conserv. 75 (3), 340–351.

Barré, P., McKenzie, B.M., Hallett, P.D., 2009. Earthworms bring compacted and loose soil to a similar mechanical state. Soil Biol. Biochem. 41 (3), 656–658.

Basso, B., Amato, M., Bitella, G., Rossi, R., Kravchenko, A., Sartori, L., Carvahlo, L.M., Gomes, J., 2010. Two-dimensional spatial and temporal variation of soil physical properties in tillage systems using electrical resistivity tomography. Agron. J. 102 (2), 440–449.

Behrends Kraemer, F., Hallett, P.D., Morrás, H., Garibaldi, L., Cosentino, D., Duval, M., Galantini, J., 2019. Soil stabilisation by water repellency under no-till management for soils with contrasting mineralogy and carbon quality. Geoderma 355, 113902.

Blanco-Canqui, H., 2011. Does no-till farming induce water repellency to soils?: No-till and soil water repellency. Soil Use Manage. 27 (1), 2–9.

Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma 326, 164–200.

Blunk, S., de Heer, M.I., Sturrock, C.J., Mooney, S.J., 2018. Soil seedbed engineering and its impact on germination and establishment in sugar beet (Beta vulgaris L.) as affected by seed–soil contact. Seed Sci. Res. 28 (3), 236–244.

Borges, J.A.R., Pires, L.F., Cássaro, F.A.M., Auler, A.C., Rosa, J.A., Heck, R.J., Roque, W. L., 2019. X-ray computed tomography for assessing the effect of tillage systems on topsoil morphological attributes. Soil Tillage Res. 189, 25–35.

Brewer, R., 1975. Fabric and Mineral Analysis of Soils. R. E. Krieger, Huntington, N.Y.

Briones, M.J.I., Schmidt, O., 2017. Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. Glob. Change Biol. 23 (10), 4396–4419.

Brunel-Saldias, N., Martínez, I., Seguel, O., Ovalle, C., Acevedo, E., 2016. Structural characterization of a compacted alfisol under different tillage systems. J Soil Sci. Plant Nutr. 16 (3), 689–770.

Camarotto, C., Piccoli, I., Dal Ferro, N., Polese, R., Chiarini, F., Furlan, L., Morari, F., 2020. Have we reached the turning point? Looking for evidence of SOC increase under conservation agriculture and cover crop practices. Eur. J. Soil Sci. 71 (6), 1050–1063.

Capowiez, Y., Gilbert, F., Vallat, A., Poggiale, J.-C., Bonzom, J.-M., 2021. Depth distribution of soil organic matter and burrowing activity of earthworms—mesocosm study using X-ray tomography and luminophores. Biol. Fertil. Soils 57 (3), 337–346.

Cheik, S., Jouquet, P., Maeght, J., Capowiez, Y., Tran, T.M., Bottinelli, N., 2021. X-ray tomography analysis of soil biopores structure under wetting and drying cycles. Eur. J. Soil Sci. 72 (5), 2128–2132.

Churchman, G.J., Foster, R.C., D'Acqui, L.P., Janik, L.J., Skjemstad, J.O., Merry, R.H., Weissmann, D.A., 2010. Effect of land-use history on the potential for carbon sequestration in an Alfisol. Soil Tillage Res. 109 (1), 23–35.

Cimpoiaşu, M.O., Kuras, O., Pridmore, T., Mooney, S.J., 2020. Potential of geoelectrical methods to monitor root zone processes and structure: a review. Geoderma 365, 114232.

Cooper, H.V., Sjögersten, S., Lark, R.M., Girkin, N.T., Vane, C.H., Calonego, J.C., Rosolem, C., Mooney, S.J., 2021a. Long-term zero-tillage enhances the protection of soil carbon in tropical agriculture. Eur. J. Soil Sci. 72 (6), 2477–2492.

Cooper, H.V., Sjögersten, S., Lark, R.M., Mooney, S.J., 2021b. To till or not to till in a temperate ecosystem? Implications for climate change mitigation. Environ. Res. Lett. 16 (5), 054022.

Cueff, S., Alletto, L., Bourdat-Deschamps, M., Benoit, P., Pot, V., 2020. Water and pesticide transfers in undisturbed soil columns sampled from a Stagnic Luvisol and a Vermic Umbrisol both cultivated under conventional and conservation agriculture. Geoderma 377, 114590.

Czarnes, S., Hallett, P.D., Bengough, A.G., Young, I.M., 2000. Root- and microbial-derived mucilages affect soil structure and water transport: mucilages, soil structure and sorptivity. Eur. J. Soil Sci. 51 (3), 435–443.

Dal Ferro, N., Delmas, P., Duwig, C., Simonetti, G., Morari, F., 2012. Coupling X-ray microtomography and mercury intrusion porosimetry to quantify aggregate structures of a cambisol under different fertilisation treatments. Soil Tillage Res. 119, 13–21.

Dal Ferro, N., Sartori, L., Simonetti, G., Berti, A., Morari, F., 2014. Soil macro- and microstructure as affected by different tillage systems and their effects on maize root growth. Soil Tillage Res. 140, 55–65.

Derpsch, R., Franzluebbers, A.J., Duiker, S.W., Reicosky, D.C., Koeller, K., Friedrich, T., Sturny, W.G., Sá, J.C.M., Weiss, K., 2014. Why do we need to standardize no-tillage research? Soil Tillage Res. 137, 16–22.

Elias, D., Wang, L., Jacinthe, P.-A., 2018. A meta-analysis of pesticide loss in runoff under conventional tillage and no-till management. Environ. Monit. Assess. 190 (2), 79.

Elliott, J.A., Cessna, A.J., Nicholaichuk, W., Tollefson, L.C., 2000. Leaching rates and preferential flow of selected herbicides through tilled and untilled soil. J. Environ. Qual. 29 (5), 1650–1656.

Fernández-Ugalde, O., Virto, I., Bescansa, P., Imaz, M.J., Enrique, A., Karlen, D.L., 2009. No-tillage improvement of soil physical quality in calcareous, degradation-prone, semiarid soils. Soil Tillage Res. 106 (1), 29–35.

Finch-Savage, W.E., Bassel, G.W., 2016. Seed vigour and crop establishment: extending performance beyond adaptation. J. Exp. Bot. 67 (3), 567–591.

Flury, M., 1996. Experimental evidence of transport of pesticides through field soils—A review. J. Environ. Qual. 25 (1), 25–45.

Galdos, M.V., Pires, L.F., Cooper, H.V., Calonego, J.C., Rosolem, C.A., Mooney, S.J., 2019. Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray Computed Tomography. Geoderma 337, 1126–1135.

Gantzer, C.J., Anderson, S.H., 2002. Computed tomographic measurement of macroporosity in chisel-disk and no-tillage seedbeds. Soil Tillage Res. 64 (1–2), 101–111.

Gao, L., Wang, B., Li, S., Wu, H., Wu, X., Liang, G., Gong, D., Zhang, X., Cai, D., Degré, A., 2019. Soil wet aggregate distribution and pore size distribution under different tillage systems after 16 years in the Loess Plateau of China. Catena 173, 38–47.

Garbout, A., Munkholm, L.J., Hansen, S.B., 2013. Temporal dynamics for soil aggregates determined using X-ray CT scanning. Geoderma 204–205, 15–22.

Ghezzehei, T.A., Or, D., 2000. Dynamics of soil aggregate coalescence governed by capillary and rheological processes. Water Resour. Res. 36 (2), 367–379.

Gonzalez-Sanchez, E.J., García, M.M., Kassam, A., Cabrera, A.H., Tarradas, P.T., Bojollo, R.C., Pisante, M., Gonzalez, O.V., Basch, G., 2017. Conservation Agriculture: Making Climate Change Mitigation and Adaptation Real in Europe. European Conservation Agriculture Federation (ECAF).

González-Sánchez, E.J., Kassam, A., Basch, G., Streit, B., Holgado-Cabrera, A., Triviño-Tarradas, P., 1 ETSIAM, Universidad de Córdoba, Spain, 2016. Conservation Agriculture and its contribution to the achievement of agri-environmental and economic challenges in Europe. AIMS Agric. Food 1 (4), 387–408.

Guo, Y., Fan, R., McLaughlin, N., Zhang, Y., Chen, X., Wu, D., Zhang, X., Liang, A., 2021. Impacts induced by the combination of earthworms, residue and tillage on soil organic carbon dynamics using 13C labelling technique and X-ray computed tomography. Soil Tillage Res. 205, 104737.

Guo, Y., Fan, R., Zhang, X., Zhang, Y., Wu, D., McLaughlin, N., Zhang, S., Chen, X., Jia, S., Liang, A., 2020. Tillage-induced effects on SOC through changes in aggregate stability and soil pore structure. Sci. Total Environ. 703, 134617.

Haas, C., Gerke, H.H., Ellerbrock, R.H., Hallett, P.D., Horn, R., 2018. Relating soil organic matter composition to soil water repellency for soil biopore surfaces different in history from two Bt horizons of a Haplic Luvisol. Ecohydrology 11 (6), e1949.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6 (1), 30.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems. Soil Tillage Res. 82 (2), 121–145.

Helliwell, J.R., Sturrock, C.J., Grayling, K.M., Tracy, S.R., Flavel, R.J., Young, I.M., Whalley, W.R., Mooney, S.J., 2013. Applications of X-ray computed tomography for examining biophysical interactions and structural development in soil systems: a review: X-ray computed tomography for soil physical properties. Eur. J. Soil Sci. 64 (3), 279–297.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ. 103 (1), 1–25.

Hunt, A.G., Sahimi, M., 2017. Flow, transport, and reaction in porous media: percolation scaling, critical-path analysis, and effective medium approximation. Rev. Geophys. 55 (4), 993–1078.

Imhoff, S., Ghiberto, P.J., Grioni, A., Gay, J.P., 2010. Porosity characterization of Argiudolls under different management systems in the Argentine Flat Pampa. Geoderma 158 (3–4), 268–274.

Jarvis, N.J., 2020. A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. Eur. J. Soil Sci. 71 (3), 279–302.

Johnson-Maynard, J., Umiker, K., Guy, S., 2007. Earthworm dynamics and soil physical properties in the first three years of no-till management. Soil Tillage Res. 94 (2), 338–345.

Kautz, T., 2015. Research on subsoil biopores and their functions in organically managed soils: a review. Renew. Agric. Food Syst. 30 (4), 318–327.

Kay, B.D., VandenBygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res. 66 (2), 107–118.

Kirkham, M.B., 2014. Infiltration. In: Principles of soil and plant water relations, Second edition. Elsevier, Amsterdam; Boston, pp. 201–227.

Kladivko, E.J., 2001. Tillage systems and soil ecology. Soil Tillage Res. 61 (1–2), 61–76.

Klik, A., Rosner, J., 2020. Long-term experience with conservation tillage practices in Austria: Impacts on soil erosion processes. Soil Tillage Res. 203, 104669.

Koestel, J.K., Moeys, J., Jarvis, N.J., 2012. Meta-analysis of the effects of soil properties, site factors and experimental conditions on solute transport. Hydrol. Earth Syst. Sci. 16 (6), 1647–1665.

Köhne, J.M., Gerke, H., Köhne, S., 2002. Effective diffusion coefficients of soil aggregates with surface skins. Soil Sci. Soc. Am. J. 66 (5), 1430–1438.

Kravchenko, A.N., Wang, A.N.W., Smucker, A.J.M., Rivers, M.L., 2011. Long-term differences in tillage and land use affect intra-aggregate pore heterogeneity. Soil Sci. Soc. Am. J. 75 (5), 1658–1666.

Kreiselmeier, J., Chandrasekhar, P., Weninger, T., Schwen, A., Julich, S., Feger, K.-H., Schwärzel, K., 2019. Quantification of soil pore dynamics during a winter wheat cropping cycle under different tillage regimes. Soil Tillage Res. 192, 222–232.

Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93 (1), 1–12.

Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkons, U., Vereecken, H., Vanderborght, J., 2019. Modeling the impact of biopores on root growth and root water uptake. Vadose Zone J. 18 (1), 1–20.

Leue, M., Gerke, H.H., Ellerbrock, R.H., 2013. Millimetre-scale distribution of organic matter composition at intact biopore and crack surfaces: Millimetre-scale distribution of organic matter. Eur. J. Soil Sci. 64 (6), 757–769.

Levanon, D., Meisinger, J.J., Codling, E.E., Starr, J.L., 1994. Impact of tillage on microbial activity and the fate of pesticides in the upper soil. Water Air Soil Pollut. 72 (1–4), 179–189.

Li, S., Lu, J., Liang, G., Wu, X., Zhang, M., Plougonven, E., Wang, Y., Gao, L., Abdelrhman, A.A., Song, X., Liu, X., Degré, A., 2021. Factors governing soil water repellency under tillage management: the role of pore structure and hydrophobic substances. Land Degrad. Dev. 32 (2), 1046–1059.

Li, Y., Li, Z., Cui, S., Jagadamma, S., Zhang, Q., 2019. Residue retention and minimum tillage improve physical environment of the soil in croplands: a global meta-analysis. Soil Tillage Res. 194, 104292.

Li, Y., Li, Z., Cui, S., Zhang, Q., 2020. Trade-off between soil pH, bulk density and other soil physical properties under global no-tillage agriculture. Geoderma 361, 114099.

Lin, H., 2011. Three principles of soil change and pedogenesis in time and space. Soil Sci. Soc. Am. J. 75 (6), 2049–2070.

Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Tillage Res. 89 (2), 210–220.

Lucas, M., Schlüter, S., Vogel, H.-J., Vetterlein, D., 2019a. Roots compact the surrounding soil depending on the structures they encounter. Sci. Rep. 9 (1), 16236.

Lucas, M., Schlüter, S., Vogel, H.-J., Vetterlein, D., 2019b. Soil structure formation along an agricultural chronosequence. Geoderma 350, 61–72.

Luxmoore, R.J., 1981. Micro-, meso-, and macroporosity of soil. Soil Sci. Soc. Am. J. 45 (3), 671–672.

Malobane, M.E., Nciizah, A.D., Mudau, F.N., Wakindiki, I.I.C., 2019. 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. Heliyon 5 (5), e01819.

Mangalassery, S., Sjögersten, S., Sparkes, D.L., Sturrock, C.J., Craigon, J., Mooney, S.J., 2015. To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? Sci. Rep. 4 (1), 4586.

Müller, K., Dal Ferro, N., Katuwal, S., Tregurtha, C., Zanini, F., Carmignato, S., Wollesen de Jonge, L., Moldrup, P., Morari, F., 2019. Effect of long-term irrigation and tillage practices on X-ray CT and gas transport derived pore-network characteristics. Soil Res. 57 (6), 657.

Müller, M., Kurz, G., Yaramanci, U., 2009. Influence of tillage methods on soil water content and geophysical properties. Near Surf. Geophys. 7 (1), 27–36.

Munkholm, L.J., Heck, R.J., Deen, B., Zidar, T., 2016. Relationship between soil aggregate strength, shape and porosity for soils under different long-term management. Geoderma 268, 52–59.

Naveed, M., Brown, L.K., Raffan, A.C., George, T.S., Bengough, A.G., Roose, T., Sinclair, I., Koebernick, N., Cooper, L., Hackett, C.A., Hallett, P.D., 2017. Plant exudates may stabilize or weaken soil depending on species, origin and time: effect of plant exudates on rhizosphere formation. Eur. J. Soil Sci. 68 (6), 806–816.

Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustainable Dev. 33 (2), 291–309.

Nimmo, J.R., 2005. In: Encyclopedia of Soils in the Environment. Elsevier, pp. 295–303.

de Oliveira, J.A.T., Cássaro, F.A.M., Pires, L.F., 2021. Estimating soil porosity and pore size distribution changes due to wetting-drying cycles by morphometric image analysis. Soil Tillage Res. 205, 104814.

Or, D., Keller, T., Schlesinger, W.H., 2021. Natural and managed soil structure: on the fragile scaffolding for soil functioning. Soil Tillage Res. 208, 104912.

Piccoli, I., Camarotto, C., Lazzaro, B., Furlan, L., Morari, F., 2017. Conservation agriculture had a poor impact on the soil porosity of veneto low-lying plain silty soils after a 5-year transition period. Land Degrad. Dev. 28 (7), 2039–2050.

Pires, L.F., Auler, A.C., Roque, W.L., Mooney, S.J., 2020. X-ray microtomography analysis of soil pore structure dynamics under wetting and drying cycles. Geoderma 362, 114103.

Pires, L.F., Roque, W.L., Rosa, J.A., Mooney, S.J., 2019. 3D analysis of the soil porous architecture under long term contrasting management systems by X-ray computed tomography. Soil Tillage Res. 191, 197–206.

Piron, D., Boizard, H., Heddadj, D., Pérès, G., Hallaire, V., Cluzeau, D., 2017. Indicators of earthworm bioturbation to improve visual assessment of soil structure. Soil Tillage Res. 173, 53–63.

Pöhlitz, J., Rücknagel, J., Koblenz, B., Schlüter, S., Vogel, H.-J., Christen, O., 2018. Computed tomography and soil physical measurements of compaction behaviour under strip tillage, mulch tillage and no tillage. Soil Tillage Res. 175, 205–216.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.-J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma 314, 122–137.

Reichert, J.M., Suzuki, L.E.A.S., Reinert, D.J., Horn, R., Håkansson, I., 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 102 (2), 242–254.

Schlüter, S., Albrecht, L., Schwärzel, K., Kreiselmeier, J., 2020. Long-term effects of conventional tillage and no-tillage on saturated and near-saturated hydraulic conductivity – Can their prediction be improved by pore metrics obtained with X-ray CT? Geoderma 361, 114082.

Schwen, A., Bodner, G., Scholl, P., Buchan, G.D., Loiskandl, W., 2011. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. Soil Tillage Res. 113 (2), 89–98.

Shakoor, A., Shahbaz, M., Farooq, T.H., Sahar, N.E., Shahzad, S.M., Altaf, M.M., Ashraf, M., 2021. A global meta-analysis of greenhouse gases emission and crop yield under no-tillage as compared to conventional tillage. Sci. Total Environ. 750, 142299.

Simms, P.H., Yanful, E.K., 2004. A discussion of the application of mercury intrusion porosimetry for the investigation of soils, including an evaluation of its use to estimate volume change in compacted clayey soils. Géotechnique 54 (6), 421–426.

Šimůnek, J., van Genuchten, M.T., Šejna, M., 2012. HYDRUS: model use, calibration, and validation. Trans. ASABE 55 (4), 1263–1276.

Smucker, A.J.M., Park, E.-J., Dorner, J., Horn, R., 2007. Soil micropore development and contributions to soluble carbon transport within macroaggregates. Vadose Zone J. 6 (2), 282–290.

Soracco, C.G., Lozano, L.A., Villarreal, R., Melani, E., Sarli, G.O., 2018. Temporal variation of soil physical quality under conventional and no-till systems. Rev. Brasil. Ciência do Solo 42, e0170408.

Soto-Gómez, D., Pérez-Rodríguez, P., Vázquez-Juiz, L., López-Periago, J.E., Paradelo, M., 2018. Linking pore network characteristics extracted from CT images to the transport of solute and colloid tracers in soils under different tillage managements. Soil Tillage Res. 177, 145–154.

Soto-Gómez, D., Vázquez Juíz, L., Pérez-Rodríguez, P., López-Periago, J.E., Paradelo, M., Koestel, J., 2020. Percolation theory applied to soil tomography. Geoderma 357, 113959.

Souza, R.C., Hungria, M., Cantão, M.E., Vasconcelos, A.T.R., Nogueira, M.A., Vicente, V. A., 2015. Metagenomic analysis reveals microbial functional redundancies and specificities in a soil under different tillage and crop-management regimes. Appl. Soil Ecol. 86, 106–112.

Taina, I.A., Heck, R.J., Elliot, T.R., 2008. Application of X-ray computed tomography to soil science: a literature review. Can. J. Soil Sci. 88 (1), 1–19.

Tuzzin de Moraes, M., Debiasi, H., Carlesso, R., Cezar Franchini, J., Rodrigues da Silva, V., Bonini da Luz, F., 2016. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. Soil Tillage Res. 155, 351–362.

USDA-NRCS (2016) Effects of Implementation of Soil Health Management Practices on Infiltration, Saturated Hydraulic Conductivity and Runoff. National Soil Survey Center.

Wairiu, M., Lal, R., 2006. Tillage and land use effects on soil microporosity in Ohio, USA and Kolombangara, Solomon Islands. Soil Tillage Res. 88 (1–2), 80–84.

Wang, X., Pan, J., Wang, K., Ge, T., Wei, J., Wu, W., 2020. Characterizing the shape, size, and distribution heterogeneity of pore-fractures in high rank coal based on X-ray CT image analysis and mercury intrusion porosimetry. Fuel 282, 118754.

Withers, P.J., Bouman, C., Carmignato, S., Cnudde, V., Grimaldi, D., Hagen, C.K., Maire, E., Manley, M., Du Plessis, A., Stock, S.R., 2021. X-ray computed tomography. Nat. Rev. Methods Primers 1 (1), 18.

Xu, D., Mermoud, A., 2001. Topsoil properties as affected by tillage practices in North China. Soil Tillage Res. 60 (1–2), 11–19.

Xue, S., Zhang, P., Bao, J., He, L., Hu, Y., Yang, S., 2020. Comparison of Mercury Intrusion Porosimetry and multi-scale X-ray CT on characterizing the microstructure of heat-treated cement mortar. Mater. Charact. 160, 110085.

Zhang, Y., Yang, B., Yang, Z., Ye, G., 2019. Ink-bottle effect and pore size distribution of cementitious materials identified by pressurization-depressurization cycling mercury intrusion porosimetry. Materials 12 (9), 1454.

Zhou, H.u., Whalley, W.R., Hawkesford, M.J., Ashton, R.W., Atkinson, B., Atkinson, J.A., Sturrock, C.J., Bennett, M.J., Mooney, S.J., Vissenberg, K., 2021. The interaction between wheat roots and soil pores in structured field soil. J. Exp. Bot. 72 (2), 747–756.