https://doi.org/10.17221/64/2023-SWR

Soil pore structure and its research methods: A review

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Citation: Wang N.N., Zhang T.B. (2024): Soil pore structure and its research methods: A review. Soil & Water Res., 19: 1–24.

Abstract: Soil pore is an important part of soil structure. According to the causes of formation, soil pores can be divided into biological pores formed by animal movement and plant root development and non-biological pores formed by dry-wet and freeze-thaw alternation or artificial tillage. The soil pore structure affects the migration of water, gas, nutrients and so on in the soil, especially the macropores can also produce water or solute preferential migration. Studying soil pores is of great significance for predicting soil hydraulic properties, reducing groundwater pollution and soil nutrient loss. Based on previous studies on soil pore structure, this paper systematically summarized the role of soil pores, influencing factors and the advantages and disadvantages of various research methods. This paper not only introduces traditional methods (including direct and indirect methods), but also summarizes the new research on soil pores combined with computed tomography (CT) technology and other science and technology in recent years. Finally, the prospect and development trend of soil pore research in the future were predicted, so as to provide reference for further research on soil pore structure.

Keywords: image analysis; influencing factors; network model; soil structure

Soil structure is defined as the spatial arrangement of soil solid components and soil pores (Dexter 1988). A good soil structure can promote the circulation of nutrients such as water and oxygen in the soil, help plant growth, and reduce the risk of soil erosion (Beven & Germann 2013); poor soil structure can limit water infiltration and gas exchange, resulting in water runoff, soil erosion and adverse anoxic conditions, limiting plant growth, and may trigger greenhouse gas emissions through anaerobic bacterial respiration (Berisso et al. 2012; Chen et al. 2014). Soil pore is the void part of soil, which is the main or even the only channel for water and solute transport in soil (Liu et al. 2001). Pore structure profoundly affects soil properties and functions. Pores in soil are mainly formed in biological activities, dry-wet or freeze-thaw alternation, organic matter decomposition and soil management, and are affected by many factors such as biological factors, natural factors and human factors (Yu et al. 2017). Pore structure parameters such as porosity, pore size, connectivity and surface area all affect the uniform distribution and flow rate of soil solution flux (Cheng et al. 2012a), and jointly control the rapid migration of water, gas, and

Supported by the National Key R&D Program of China (Grant No. 2023YFD2001404).

https://doi.org/10.17221/64/2023-SWR

chemical substances in the soil (Meng et al. 2020). At the same time, soil pore structure parameters also affect cation exchange and cation migration in soil, and these parameters determine the relationship between convective transport and diffuse ion transport. Maintaining good porosity and pore size distribution is an important consideration for soil health management. Studying soil pore structure is of great significance for predicting soil hydraulic properties, reducing soil nutrient loss and groundwater pollution, formulating reasonable irrigation schemes, and improving agricultural water use rate (Isensee et al. 1988; Liu et al. 2001). We summarize the significance of common soil pore characteristic parameters (Table 1).

Macropores in soil can also reduce surface runoff, increase soil permeability, produce preferential transport of water and solute, promote plant growth and increase crop yield. The soil macropores with equivalent pore diameter greater than 1 mm significantly affect the flow rate and flow rate of water in the soil and can be used as an important channel for conducting surface stagnant water and suspended water (Luxmoore 1981; Rasiah & Aylmore 1998). Although soil macropores account for only 0.1–5% of soil volume, they can conduct 90% of water flow (Wu et al. 2009). If the content of macropore structure in the soil is more, the soil has better aeration and permeability, which is conducive to crop growth (Cheng et al. 2012a); however, if the pores in the soil are too large, water, gas, and chemical substances will quickly pass through the soil without interacting with the soil, that is, priority migration occurs, which may cause groundwater pollution and nutrient loss (Sun et al. 2015). A study found that the larger the average tortuosity of macropores in the soil, the slower the water infiltration rate; the larger the roundness rate of soil macropores, the better the three-dimensional connectivity, and the better the infiltration effect. Quantitative study of soil macropores and accurate description of pore space will help to understand the mechanism of water and solute transport in soil (Luo et al. 2010). At present, there is no uniform standard for the size classification of soil pores at home and abroad. We summarize the definition criteria of some common macropores (Table 2).

There are a variety of research methods for soil pores. In general, these traditional methods can be divided into two categories: (1) indirect method for inferring pores by correlation curves or models (such as water retention curve method, mercury intrusion method, etc.); (2) direct method of directly

Table 1. Definition of soil pore characteristic parameters

Soil pore characteristic parameters	Definition	References
Equivalent pore diameter	pore size equivalent to a certain soil water suction	Cheng et al. (2012b)
Porosity	percentage of pore volume to total soil	Luo et al. (2010); Meng et al. (2017)
Void ratio	the ratio of pore volume to solid particle volume	Meng et al. (2017); El-Husseiny (2021)
Roundness	degree of surface area of pores approaching the theoretical circle	Guo et al. (2018)
Tortuosity	ratio of actual length of pores to the length of straight lines	Müller et al. (2018)
Inclination angle	angle between vertical direction of pores and ground plane	Stewart et al. (1999); Hu et al. (2018)
Number of node	number of intersections connecting two pore branches	Luo et al. (2010)
Number of path	number of continuous and independent pores penetrating top and bottom of column	Luo et al. (2010)
Connectivity	number of independent paths between two points in pore space, and the number of pores connecting the surface and bottom of soil	Larsbo et al. (2014)
Critical pore diameter	the bottleneck in the pore connection from top to bottom, and it corresponds to the diameter of the largest sphere that could be moved from top to bottom through the pore system	Koestel and Schlüter (2019)
Euler number	it is used to measure the number of connections that a structure can disconnect before splitting into two independent objects	Lucas et al. (2019)

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extracting soil pores for quantification (such as soil slicing method, computed tomography (CT) method, etc.). The biggest advantage of the traditional soil pore research method (other methods of part 3 besides CT scanning method) is cost saving, simple operation and easy to understand; however, high standard experimental conditions and complicated sample preparation process are required, and the soil pore structure will be destroyed to varying degrees, resulting in inaccurate pore parameters. Some test reagents will also cause harm to human body (Dal Ferro et al. 2012; Sasanian & Newson 2013). In addition, due to the randomness, complexity, uncertainty and certain autocorrelation of soil pore structure in spatial distribution, traditional research methods cannot accurately describe and quantitatively describe it (Martín et al. 2017; Zhang et al. 2019). In addition to these traditional methods, we also briefly summarize the current research progress of scholars on soil pores. They mostly combine tomography technology and use more advanced software or science and technology to further study the changes of soil pores under the influence of different factors. For example, the neural network model was used to segment the pore threshold, the correlation function was used to describe the soil pore structure, or the soil physical property model was established. Although these methods also have their own defects and scope of application, the soil pore structure characteristics obtained by these methods are more accurate and detailed than those obtained by traditional methods. This paper summarizes the previous studies on soil pores, and briefly reviews the role, causes, influencing factors and specific research methods of soil pores, in order to provide reference for further research on soil pore structure.

INFLUENCING FACTORS OF SOIL PORE

The causes of soil pore structure are complex and affected by many factors (Omoti & Wild 1979). This section will be described in detail from three aspects: biological, natural and human factors. Studies have shown that compared with the cracks formed by dry-wet or freeze-thaw alternation, the tubular pore structure formed by plant root activity and animal movement is more stable, and the inner wall is smoother, which is more conducive to soil water infiltration (Hagedorn & Bundt 2002). Soil pores formed by biological activities such as roots, ants, and earthworms can remain for a longer time without external interference (Zhang et al. 2015). Soil pores

Table 2. Definition standard of soil macropores

Definition method	Founder and year	Macropore definition standard	References
Defined by equivalent pore diameter	Luxmoore 1981	ECD > 1 mm	Luxmoore (1981)
	Beven and Germann 1982	0.3 mm < ECD > 3 mm	Beven and Germann (1982)
	Kay 1990	ECD > 30 μm	Kay (1990)
	Singh et al. 1991	ECD > 1.6 mm	Singh et al. (1991)
	Vermeul et al. 1993	ECD > 0.085 mm	Vermeul et al. (1993)
	Taboada et al. 1998	ECD > 100 μm	Taboada et al. (1998)
	Shi and Liu 2005	ECD > 2.4 mm	Shi and Liu (2005)
	Soil Science Society of America 2006	ECD > 75 μm	Cameron and Buchan (2006)
	Wu et al. 2007	ECD > 0.3 mm	Wu et al. (2007)
	International Union of Pure and Applied Chemistry (IUPAC) 2009	ECD > 50 nm	Wang et al. (2009)
Defined by capillary potential	Mosley 1982	CP > –5 000 Pa	Mosley (1982)
	Luxmoore 1981	ECD > 1 mm, CP > –3 000 Pa	Luxmoore (1981)
Defined by function	Skopp 1981	pores that allow full mixing and conduction of water and solute	Skopp (1981)
	Liu et al. 2001	pores between aggregates that can provide preferential flow paths	Liu et al. (2001)
	Li et al. 2007	pores that can produce preferential migration	Li et al. (2007)

ECD – equivalent pore diameter; CP – capillary potential

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formed by plant root activity and animal movement are collectively referred to as biological pores. Most of the biological pores are connected cylindrical pores, which are the sites of microbial activity and nutrient mineralization, and are the preferential flow paths for root growth, gas exchange and water infiltration (Kautz 2015).

Biological factors

Plant root activity. Plant root activity is one of the most important factors affecting the formation of soil pores (Zhang et al. 2015). The roots of plants form roots of different sizes through a series of growth processes (thickening, stretching, branching, etc.), which can change the soil structure, and after the death and decay of the root system, the tubular cavity of the bark is formed, thus forming a pore structure mainly in the vertical direction (Kautz 2015; Li 2017). For example, Gaiser has found more than 4 000 vertical root holes in 1 hm^2 of woodland (Gaiser 1952). In primitive forests, the roots of some trees can form huge vertical pores with a maximum diameter of tens of centimetres after death (Shi et al. 2005). The pores formed by plant root activity can exist in the soil for a long time without human interference, the pores produced by root activity can exist in 30% clay soil for 50–100 years (Bouma & Wösten 1984). In addition, the root size and pore structure formed by different types of vegetation in different geographical environments are also different. For example, the roots of broad-leaved forests are more developed than coniferous forests, and soil pores are more likely to form after death and decay (Shi et al. 2007; Li 2017). The importance of biological pores to root elongation varies with soil properties. In relatively compact subsoil, roots mainly grow in biological pores. Roots growing along biological pores can eventually bypass the compacted soil layer and re-enter the bulk soil in the less compacted soil layer (Ehlers et al. 1983). Therefore, root growth through biological pores can facilitate the exploration of water and nutrients stored in deep bulk soils (Kücke et al. 1995). Compared with trees, the roots of herbaceous plants are usually shallow. Their roots mainly affect the surface pores of the soil and do not form large channels or pores in the deep soil. The root depth can vary with plant species, soil types and environmental conditions, but it is usually not deeper than 30 cm. Some herbaceous plants may form a fine root network affecting soil structure in the upper soil through rhizomes or shallow roots (Webb et al. 2022). The roots of shrubs are generally between the roots of trees and herbaceous plants in depth. Their roots can affect deeper soil pores below the surface soil. The effect of shrubs on soil porosity will depend on their specific root architecture and the soil conditions in which they grow. The roots of crops are concentrated in the plough layer, generally not as deep as trees or shrubs (Páez-Bimos et al. 2022). The effects of different types of plants on soil porosity vary depending on their root characteristics, including root depth, diameter and configuration. Compared with other plants, trees with deep roots have the potential to affect soil pores to a greater depth. However, the specific effects of any plant on soil porosity will also depend on local soil conditions, climate, and management practices.

Animal movement. In addition to root activity, animal movement in soil is also one of the important causes of pores (Flury & Flühler 1994; Mando & Miedema 1997). Various animals (such as earthworms, ants, rodents, millipedes, small crustaceans, etc.) in the soil have formed stable pore channels by drilling in and out. Among them, ants and earthworms are the two most important animals that form pore structures (Green & Askew 1965). Ants can find food by digging holes or build living space and storage rooms in the soil to form soil pore structure. The pore diameter generated by ant activity is about 2–50 mm, and the depth can reach more than 1 m (Mando & Miedema 1997). In northern Burkina Faso, West Africa, termite activity has transformed the original compact soil particles into chambers and channels, which account for more than 60% of the pores in the 0–10 cm layer. Earthworm activity can also produce soil pores. Compared with ants, earthworm activity produces larger pore diameter and better connectivity, which can help plants increase root value (Bottinelli et al. 2015). The pore diameter produced by earthworm activity is about 2–11 mm, and the average depth can reach more than 70 cm. When the weather is too cold or too hot, the depth can reach 1.8 m; soil pores generated by animal activities can exist for hundreds of years without human interference (Flury & Flühler 1994; Langner et al. 1999; Zhang 2013).

Natural factors

Dry-wet alternation. The number and intensity of dry-wet alternation cause pores in the soil (Zhang et al. 2017a). Because the dry-wet alternation changes the soil moisture, resulting in soil expan-

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sion or contraction, it changes the original soil pore structure (Ou et al. 1999a). When the clay soil is dry, the soil produces large cracks due to the decrease of water content. The fissures formed by heavy clay are difficult to close even if they are wet for a long time (Lewis 1977; Bouma 1981; Tokunaga 1988). The dry-wet alternation caused by rainfall is also a common way to change the soil pore structure. When the rain falls, the mechanical pressure and the surface rainwater infiltration cause the surface soil structure to be destroyed, and the soil porosity decreases, but the pore structure of the deeper soil layer (below the surface soil) is less affected (Hu 2003). The dry-wet alternation after tillage changed the structure and pore-related functions of the field soil, but the natural consolidation of soil caused by the dry-wet alternation after tillage gradually decreased (Zhang et al. 2017a). Peng et al. (2016) studied the relationship between soil shrinkage and dry-wet alternation in two kinds of paddy fields and found that soil shrinkage and cracking in paddy fields were significantly affected by dry-wet alternation, and the intensity of dry-wet alternation had greater influence on soil pores than dry-wet frequency and order. Bodner et al. (2013) studied the field soil and quantified the dry-wet alternation of the field water content time series by spectral analysis. The results showed that the dry-wet alternation increased the macroporosity and reduced the pore heterogeneity. The drying period increased the frequency of smaller pores, and the dynamics of pore size distribution can be predicted from the wetting-drying model.

The response of different types of soil to dry-wet alternation varies due to its characteristics. For clay soil, when wet, clay soil absorbs water and expands, which helps to improve pore structure and increase porosity. During drying, the clay soil may crack and collapse, resulting in surface cracking, reducing porosity and increasing the risk of erosion. Loam and sandy soils usually have good water permeability, so water can penetrate into the soil quickly during wetting, which helps to maintain the pore structure. When dry, loam and sandy soil usually maintain good drainage, but easy to lose water and reduce porosity. Soils rich in organic matter are usually able to maintain moisture during wetting, and are conducive to microbial activity, which helps to maintain soil pore structure; it is also relatively stable during drying because organic matter has better water retention ability and can slow down water loss (Zhang et al. 2018; Guo et al. 2023).

Freeze-thaw alternation. Compared with dry-wet alternation, freeze-thaw alternation has a more significant effect on the formation of soil pores and preferential flow (Ou et al. 1999b). The soil pores produced by freeze-thaw alternation are mainly macropores such as cracks (Beven & Germann 1982). Soil pores in cold regions are closely related to temperature amplitude and soil water content. Studies have shown that the larger the soil temperature amplitude, the higher the soil water content, and the more conducive to the formation of macropore structure in soil. Zhao and Hu (2020) found that with the increase of freeze-thaw alternation times, the content of frost heave mounds and inter-mound soil macropores in alpine grassland showed a trend of decrease – increase – decrease. Li et al. (2022) found that frost heave can significantly increase the soil porosity of saline-alkali soil. On the saline-alkali soil with determined water content, the porosity increment increases monotonously with the decrease of freezing temperature. The lower the freezing temperature, the more obvious the frost on the saline-alkali soil and the more developed the pores (Li et al. 2022). According to the research of Ma et al. (2021), with the increase of freeze-thaw alternation times, the total porosity of soil aggregates increases, and the number of pores decreases after a certain fluctuation. The freeze-thaw alternation also has a significant effect on the pore shape, and the slender porosity increases with the increase of freeze-thaw alternations (Ma et al. 2021). Freeze-thaw intensifies the development of a double pore structure. Compared with freezing time, freezing temperature plays a more important role in the change of porosity structure. With the decrease of freezing temperature, the surface fractal size and volume fractal size on a small pore size scale decrease slightly (Zhou & Tang 2018).

Freeze-thaw alternation has different effects on different types of soil pore structure and porosity. For clay, during freezing, water freezes in the clay soil, causing the particles to expand, possibly destroying the pore structure. Clay soil is usually more susceptible to freezing, resulting in hard soil. During thawing, water re-enters the soil, resulting in particle shrinkage and soil collapse. This may lead to cracking and potholes on the soil surface and increase the risk of erosion. For sandy soil and loam, loam and sandy soil are usually less affected by freezing, because their particles are large and are not susceptible to freezing and thawing. Therefore,

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the pore structure may be relatively stable. During thawing, the soil may be more likely to retain moisture because they usually have better drainage and are not prone to collapse. The water status of the soil also plays an important role in the freeze-thaw cycle. The moisture content in the soil can affect the severity of freezing and thawing, and whether it will cause soil collapse or cracking. Soils rich in organic matter may be more susceptible to freeze-thaw cycles, because organic matter contains water, which is conducive to the freezing and thawing process. Freezing and thawing may lead to decomposition of organic matter, gas production and soil erosion (Tang & Yan 2015; Qin et al. 2021; Xu et al. 2021).

Human factors

Tillage method. Tillage destroys the continuity of soil surface pores, destroys the existing soil structure, forms the pore space between large aggregates with unstable structure, and makes the pores tend to develop more stable pore size distribution (Mapa et al. 1986). Different tillage methods or wheel traffic compaction may lead to changes in the pore system in space and time. Wang and Chu (1992) also found that tillage soil has more pore structure than no-tillage soil. In addition, soil pores formed by tillage can be restored by dry-wet alternation (Urbina et al. 2019). Chen et al. (2012) showed that the total porosity of soil in no-tillage soil was smaller than that in tillage soil, but the pore content in no-tillage soil was more than that in tillage soil in 0–5 and 20–30 cm soil layers, and less than that in 5–20 cm soil layer. Schlüter et al. (2018) showed that compared with conventional tillage, reduced tillage would lead to a decrease in the saturated hydraulic conductivity of the soil at a depth of 13–23 cm, and ploughing could cause periodic loosening of the soil, which not only increased soil macroporosity and macropore connectivity, but also increased soil saturated hydraulic conductivity. The increasing weight of agricultural machinery increases the risk of subsoil compaction, which has a negative impact on soil porosity and gas transport characteristics, and this effect is difficult to mitigate through soil tillage and natural loosening (Berisso et al. 2012). In addition, livestock trampling can also lead to soil compaction. Romero-Ruiz et al. (2023) studied a model to simulate the effect of animal trampling on the internal pores of soil, and successfully demonstrated the volume density, macropore porosity and saturated hydraulic conductivity of compacted soil.

Different tillage methods have different effects on different types of soil pore structure and porosity, which depend on soil type, climatic conditions, agricultural practices and soil management methods. For clay soil, deep ploughing may improve the permeability of clay soil, reduce soil compaction and increase water infiltration. However, excessive deep ploughing may lead to soil erosion and loss of organic matter, thus affecting pore structure. Light tillage and conservation tillage can reduce the risk of soil erosion, help maintain soil structure and organic matter, and improve pore structure. Crop rotation and mulching can help to improve the structure of clay soil, reduce soil compaction and increase water infiltration. For sandy and loamy soils, deep ploughing may destroy soil aggregates and stable pore structures in loamy and sandy soils, leading to soil collapse and erosion. Light tillage or conservation tillage helps to maintain soil structure and reduce the risk of soil collapse and water loss. Rotation and mulching crops help to maintain organic matter and stable pore structure in loam and sandy soil and improve soil quality. No tillage or less tillage can help to maintain soil structure, increase the stability of soil aggregates, increase porosity and water permeability (Sarkar & Singh 2007; Reynolds et al. 2014; Yang et al. 2021).

Fertilization method. Soil organic matter can have a positive impact on soil structure by promoting the formation of aggregates, reducing bulk density and increasing porosity. Fertilization affects the internal pore structure of soil by changing the physical and chemical properties of soil (Xu et al. 2020). Fertilizers change the composition of aggregates and particles between soils, and the effects of different fertilizer types and different fertilizer amounts on soil pores are also different (Sun et al. 2015). Studies have shown that long-term application of chemical fertilizers will reduce soil porosity, resulting in soil compaction and poor tillage. The combined use of chemical fertilizers and organic fertilizers can increase soil porosity, improve soil environment, and help prevent soil degradation (Lai et al. 1992; Bronick & Lal 2005; Lan et al. 2020). The application of organic fertilizer is an important way to improve soil structure. The application of various organic fertilizers can reduce soil bulk density, improve soil pore structure in the field, improve soil porosity and connectivity, and increase the number of macropores. However, the specific effects of various organic materials are different, and the effect of straw plus organic ferti-

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lizer is the most obvious (Xuan et al. 2022). Organic management (application of organic fertilizers while avoiding chemical fertilizers and pesticides) not only increases the total macroporosity in the soil to the optimal range for plant growth but also optimizes the pore size distribution by increasing the relative porosity of the transmission pores (50–500 μm) (Wang et al. 2021a). Xu et al. (2020) studied the change trend of macropores under long-term application of organic fertilizer in greenhouse vegetable soil. The results showed that the application of organic fertilizer could increase the number of soil macropores, but its effect may depend on the amount of application. The application of organic fertilizer has a positive effect on soil physical properties (Hondebrink et al. 2017; Xu et al. 2020).

Different fertilization methods have different effects on different types of soil pore structure and porosity. These effects are closely related to soil type, fertilization type, fertilization amount, fertilization time and soil management methods. For clay, excessive fertilizer application may lead to nutrient leakage and soil acidification, which may adversely affect the pore structure. Nutrient leakage may scour the clay in the soil, resulting in the destruction of evenly arranged pores. Organic fertilizer can improve the structure of clay soil and increase the content of soil organic matter. This helps to improve pore structure and increase water retention and permeability. For sandy and loamy soils, chemical fertilizer application can increase the supply of nutrients in the soil, but attention should be paid to avoid excess nutrients to reduce nutrient loss (Lan et al. 2020; Wang et al. 2021b). Organic fertilizer is also beneficial to loam and sandy soil, which can increase soil organic matter, improve soil pore structure and water retention capacity. The mixed fertilization method combines the rapid release of nutrients from chemical fertilizers and the long-term release of nutrients from organic fertilizers. This helps to provide a comprehensive nutrient supply while maintaining the pore structure of the soil. The application of organic fertilizer and biological fertilizer can increase the content of soil organic matter and increase soil biological activity. This helps to improve soil pore structure and increase stable soil aggregates (Zhou et al. 2013).

Fertilization usually provides the nutrients needed by plants, such as nitrogen, phosphorus, potassium, etc. This can stimulate the growth of microorganisms because they need these nutrients for metabolism and reproduction. The increase of microbial activity and growth will lead to changes in soil structure (Niu et al. 2020). For example, fungal hyphae can bind soil particles together and enhance soil agglomeration. In some cases, the improvement of aggregates will lead to an increase in porosity, which is due to the formation of stable soil aggregates, resulting in larger pores. In the presence of nutrients, the increase of biological activity and the decomposition of organic matter also contribute to the formation of stable soil structure, thus affecting porosity. Different types of fertilization (organic fertilizer, chemical fertilizer, mineral fertilizer, etc.) can have different effects on the community structure of soil microorganisms. For example, organic fertilizer usually promotes the growth of probiotics, and too much nitrogen fertilizer may lead to an increase in nitrifying bacteria. The use of certain fertilizers may change the pH of the soil, which may also affect microbial activity and diversity. Fertilization usually improves plant growth, thereby increasing root biomass and root exudates. This can improve soil structure and increase soil porosity (Luo et al. 2023). Biochar, as a soil amendment, enhances soil stability and water holding capacity. It promotes the formation of stable aggregates and can form macropores in the soil. The porous structure of biochar itself increases the total porosity of the soil, provides a habitat for soil microorganisms, and improves aeration. Proper use of biochar can improve soil pore structure, especially in sandy soils, which can help alleviate the problems of poor soil fertility and insufficient water retention capacity (Palansooriya et al. 2019). The use of fertilizers and biochar can affect the microbial community and porosity in the soil, but these effects depend on the specific fertilizer and biochar type, dosage, and soil environmental conditions. Rational use of fertilizers and biochar can help improve soil pore systems.

Other factors

In addition to the above factors, the inherent nature of the soil, soil texture, soil structure, soil colloid content, organic matter content, gravel content, humidity, pH value, etc. can affect plant growth and animal activities, thereby affecting the formation of pores in the soil (Ou et al. 1999a; Liu et al. 2001; Sun et al. 2015). The characteristics and distribution of soil pores vary with the seasons of the year, which is due to a variety of factors, including precipitation, temperature, vegetation growth and soil biological activities. Spring is the beginning of the

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growing season of plants. Soil temperature rises, vegetation grows rapidly, roots begin to expand, and root exudates begin to affect soil structure. Spring is usually accompanied by more precipitation, which helps to improve soil water retention and pore system, because water penetrates the soil and fills the pores. Summer is usually a season of high temperature and high evaporation, and the water in the soil may decrease, resulting in the shrinkage of the pore system in the soil. The vegetation kept growing in summer and the roots further expanded, but the pores in the soil may become drier. Autumn is usually the season when precipitation gradually decreases, and the soil begins to become drier, but still maintains more pores. Deciduous leaves and plant residues began to enter the soil, providing raw materials for the decomposition of organic matter in the soil, which helped to increase the content of soil organic matter. Winter is usually accompanied by low temperature, and the water in the soil may freeze, resulting in more orderly pores. This contributes to the stability of soil structure. Vegetation growth slowed down, root activity decreased, and the effect on soil pores decreased (Bryk et al. 2017).

TRADITIONAL SOIL PORE RESEARCH METHODS

The size, shape and number of soil pores all affects the infiltration of water in soil and the water holding capacity of soil. The methods used to study soil pores mainly include water retention curve method, mercury intrusion method, CT method, soil slicing method, etc. (Bouma 1981; Cheng et al. 2012a; Li 2017). Although these methods can quantitatively analyze soil pores, each method has its applicable conditions and advantages and disadvantages. This section mainly divides these methods into indirect methods and direct methods, and introduces the principles, advantages and disadvantages of different soil pore research methods.

Indirect methods

Marker penetration curve method. Marker penetration curve method is one of the most commonly used methods for indirect measurement of soil pore structure. The principle is to infiltrate a solution containing ions (such as Cl^-, Br^- and NO_3^-, etc.) or other dyes with weak binding capacity to the soil into the soil. According to the function curve between the concentration of the marker in the soil outflow solution and the volume of the outflow liquid, combined with the basic water flow equation and the Poiseuille equation, the structural parameters such as soil pore size at a certain depth are indirectly calculated. When using intact soil columns for the Marker Penetration Curve method, the size of the column should be sufficient to represent the vertical variability of soil properties. The column diameter can vary but is often in the range of 5–10 cm. The height of the column should typically be at least 20–30 cm to allow for significant penetration and measurement of marker movement (Parker 1984; Moore et al. 1986). Luxmoore et al. (1990) studied the physical and chemical characteristics of soil pores at two different forest sites using different marker ions to penetrate soil. Chen and Shi (2006) also used this method to study the pore variation range and dominant flow in the soil under different three kinds of vegetation in the upper reaches of the Minjiang River and the characteristics of forest macropores. The cost of estimating soil pore structure by marker penetration curve method is low, and the experimental operation and data analysis are simple. However, this method can only estimate the pore structure in soil by outflow velocity and marker concentration, which causes certain errors.

Soil tension infiltrometer method. The soil tension infiltrometer method is to control the water head gradient of the infiltration liquid by the tension infiltrometer, and obtain the water conductivity of the soil pores under different water head gradients. The pores are classified according to the capillary action equation, and the porosity and the number of pores per unit area under different water head conditions are calculated by Poiseuille equation. In field studies, the size of the sampled area will depend on the research objectives. In laboratory experiments, the sample volume can vary depending on the equipment available and the desired resolution. Soil samples may range from a few litres to tens of litres, with the sample size adjusted based on the specific needs of the experiment (Watson & Luxmoore 1986; Perroux & White 1988). Watson and Luxmoore (1986) used a tension permeameter to control water infiltration in order to estimate the pore density in the forest watershed and found that the water flux through the matrix pore space and macropores was logarithmically normal in space. Perroux and White (1988) used a double-ring infiltrometer to measure soil water infiltration under hydrostatic pressure to estimate soil pore structure. The advantages of soil tension

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infiltration meter method for determining soil porosity are low cost and simple operation. However, this method estimates soil porosity by measuring hydraulic conductivity, so the measurement results are not accurate enough.

Water retention curve method. By measuring the water retention curve, a series of soil water content and soil suction values are obtained. According to the capillary rise formula, the soil pore diameter (equivalent pore diameter) corresponding to the corresponding suction can be obtained. It is suitable for measuring soil pores with equivalent pore diameter less than 300 μm. Radulovich et al. (1989) obtained the water retention curve by regularly measuring the flow conditions from the drainage state to the saturated steady state through the flow of the soil core, and thus estimated the distribution of pores in the soil. Chen and Shi (2005) studied the relationship between soil hydraulic conductivity and porosity under evergreen broad-leaved forest in Jinyun Mountain through water retention curve. Hajnos et al. (2006) quantized the pore size distribution of orchard soil using four measurement techniques, including water retention curves, to improve the multi-domain simulation of water and solute flow and pore-dependent adsorption. Zhang et al. (2022) measured the water retention curves of subgrade aggregates with different clay fine particle contents, and speculated the pores of soil aggregates with different fine particle contents. Ferreira et al. (2019) also used the water retention curve to analyse the soil structure changes caused by lime, and concluded that lime no-tillage reduced the macroporosity of shallow soil and expanded the pore volume of surface pores. According to the water retention curve method, the estimation of soil pores is simple and cost-effective. However, it takes a long time and requires a large amount of soil. In the process of soil saturation, the soil pore structure will be changed due to soil expansion, resulting in a large error in pore measurement.

Mercury intrusion method. Mercury cannot enter the soil without pressure. Only when the external pressure reaches a certain value, mercury can enter the soil pores of the corresponding pore size. Based on this principle, the mercury intrusion method is to estimate the pore volume in the soil by pressing the volume of mercury into the soil under different pressures. Mercury intrusion method is also a method to characterize porous materials with pore range from 500 μm to 3 nm (Rouquerol et al. 2012). Sasanian and Newson (2013) used mercury intrusion method to study the effect of water content change on the pore size distribution of two kinds of clay, and confirmed that there are two kinds of macropores (intra-cluster pores and inter-cluster pores) in the material, and the pore volume in the clay aggregate is independent of the water content, but the pore volume between the clay aggregates changes proportionally with the change of water content. Li and Zhang (2009) used mercury to invade soil pores and quantitatively determined soil pore structure by showing the relationship between cumulative pore volume and pore size. Zhou et al. (2010) used mercury intrusion method to study the changes of soil pores under different consolidation pressures and obtained that the original silt soil has large pores, and the pore distribution is mainly small pores. With the increase of consolidation pressure, the pore volume in the soil decreases significantly, the aggregates in the soil collapse and slip, the pores in the aggregates are compacted, and the pore distribution gradually develops to micropores and ultramicropores. Dal Ferro et al. (2012) combined mercury intrusion method and X-ray micro computerized tomography to study the total porosity and pore size distribution of soil aggregates under different fertilization conditions. The results showed that mercury intrusion method can detect micropores (30–6.25 μm) that cannot be displayed by micro-CT, and soil fertilization can affect pore morphology and pore network structure (Dal Ferro et al. 2012). Zong et al. (2015) used nitrogen adsorption method, mercury intrusion method and X-ray scanning method to evaluate soil pores in different soil formation processes, and found that the combination of the three can quantify the porosity and pore size distribution of soil under various voids. Mercury intrusion method has the advantages of short measurement time and wide measurement range. However, mercury is toxic and can cause harm to the body of surveyors, and the soil measured by mercury intrusion method is difficult to reuse.

Model fitting method. The study of soil pore structure can also be based on the mathematical model of water and solute transport in pores established by scholars at home and abroad, such as HYDRUS, SALTMED, SALTMOD, etc. (Cheng et al. 2012b). Model fitting method can obtain the internal structure of soil pores, which shows great superiority in the study of soil connectivity. However, various models have simplified the geometric morphology and topological structure of soil pores, resulting in a certain

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difference between the model and the actual soil pores (Cheng et al. 2012a; Meng et al. 2020).

Direct methods

Direct observation method. The direct observation method refers to digging the soil profile at different depths, cleaning the surrounding debris, exposing the soil pores, and then counting the soil pores by photographing the soil surface, depicting the soil surface shape or other artificial counting methods. Edwards et al. (1993) darkened the pores by using lights to illuminate the soil plane from a certain angle and then photographed the soil cross-section to screen and count the soil pore structure by the colour depth in the photo. Logsdon et al. (1990) placed a transparent plastic film on the surface of the soil and used a pen to trace the outline of the soil pores on the plastic film, and then counted the number and area of pores in the soil according to the shape of the plastic film to estimate the soil porosity. Although these methods are simple and intuitive, soil pore structure can be obtained without other instruments and equipment. However, due to the damage to the soil caused by the excavation of the soil, and the limited accuracy of the naked eye observation, only the soil pores visible to the naked eye can be analysed, and the influence of other human factors on the test will lead to statistical uncertainty, so the direct observation method is gradually abandoned by scholars.

Dye tracer method. The dye tracer method refers to the full infiltration of tracers such as bright blue, methylene blue, or other chemical elements in the soil after mixing with water, and then excavating the profile to determine the path characteristics of the tracer in the soil, thereby obtaining the development of soil pore structure (Andreini & Steenhuis 1990). In the 1970s, Ehlers (1975) first used methylene blue as a tracer to apply it to the pre-wetted soil area. After half an hour, the plastic sheet was placed on the cross section of different depths of the soil to mark the stained area. Through image processing system and visual development language image analysis, the pore area, pore size and centre of gravity position were obtained. Ghodrati et al. (1999) selected a nitrogen-containing dye Acid-Red as a tracer. After six days of application of the dye, different soil profiles were excavated to check the vertical distribution of the dye. The dye tracer method is simple and convenient to operate, and the dye increases the visibility of the pore structure, which is more convenient to observe, and it is suitable for both indoor test and field test. However, this method is often combined with the direct observation method, and the results are limited by the image resolution, and the excavation of the soil profile is bound to cause damage to the soil structure, so it is difficult to obtain the original soil pore structure. Secondly, the dye will pollute the soil, resulting in poor repeatability of the test.

Filling irrigation method. The filling irrigation method is the use of consolidated material (such as resin, hardening agent, etc.) and other infiltration materials mixed evenly poured into the soil, after its complete hardening, and then remove the solidified material surrounding the soil, get the soil pore shape, size, quantity, etc. McBratney et al. (1992) used resins of different colours to fill the soil, and the soil pore structure model was obtained after the resin was hardened, and the model obtained by image processing and measurement technology was consistent with the soil geometry model obtained by soil pouring. Tschinkel (1987) used thin gypsum slurry to pour into the ant dens with frequent ant activities, and obtained the ant den model in the soil after hardening. Although the filling irrigation method can obtain a complete model of soil pore structure, it is difficult for consolidation materials such as resin to completely penetrate all pores before solidification, resulting in inaccurate statistical results, and the filling and pouring method has a narrow scope of application, and it is difficult to count the soil pore structure with poor connectivity.

Soil slicing method. The soil slicing method refers to placing the treated soil column into a curing agent such as resin or rosin resin (epoxy resin is used by domestic scholars in recent years). After it is completely solidified, the soil column is taken out, and the soil sections at different depths are cut into soil slices. Digital images are obtained by digital camera or other tools, and the soil pore structure is analysed according to the pictures (Jongerious & Heintzberger 1975). In addition, the samples can be stained with gentian violet, Rhodamine B, methylene blue, etc., before making the sample sheet, which is helpful to clearly observe the soil structure. Later, with the emergence of multi-disc automatic slicing technology, scholars can quickly prepare soil sheet samples. Soil slicing is the main method and effective method for early quantitative study of soil pores. In 1996, Ringrose-Voase successfully measured the soil macropore geometry and roughly quantified the soil pore space by image analysis of impregnated soil slices (Ringrose-Voase 1996). Li et al. (2003)

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used the digital image of soil slices to quantitatively evaluate the variability and complexity of soil pores. Ma (2005) studied the effects of different infiltration heads on soil surface porosity and profile porosity through soil slice and digital image analysis technology. Yu et al. (2019) also studied the effect of soil pores on the adsorption of organic matter through soil slices. The idea of soil slice method is simple and easy to understand and can obtain soil pore structure at different depths. However, its operation is complicated. High temperature treatment may cause changes in soil structure, and only two-dimensional soil pores can be obtained. The three-dimensional model deduced from the two-dimensional structure has a large deviation from the actual value.

CT scanning method. The early scanning CT method uses X-ray CT scanning equipment to scan the sampled soil to obtain each CT slice image of different soil samples. Through the analysis of the image, the pores of each slice are obtained. Through a series of tedious single slice statistics, the volume of the soil sample can be roughly calculated, which is the so-called two-dimensional analysis and cluster analysis of the slice. CT imaging is effective in visualizing and characterizing pores in the micrometre to millimetre range. Pores smaller than the micrometre scale (nanometre-sized pores) are typically beyond the resolution of most CT scanners. The first automatic segmentation algorithm was developed in the 1970s (Otsu 1979). It was originally used to process scanning electron microscopy (SEM) images and obtain related parameters such as pores, porosity, pore size distribution, and pore perimeter limited by image resolution. In the 1990s, Anderson et al. (1990) used CT technology to study and evaluate soil pores. Peyton et al. (1992, 1994) and Zeng et al. (1996) measured the macropore diameter and porosity of soil by X-ray CT scanning, and described the macropore structure by fractal geometry. Perret et al. (2000) studied the application of CT scanning technology in determining the distribution of soil macropores, and pointed out that this method can more clearly show the flow path of dye tracer through soil macropores. In 1987, Sasov used computed tomography to study the microstructure of soil, but on the computer at that time, it took seven minutes to reconstruct a slice (Abrosimov et al. 2021). The low computational power of slice reconstruction, phase segmentation and volume calculation is a serious problem in the early development of tomography. However, with the development of science and technology, the accuracy of CT has been continuously improved, and various image analysis software has been continuously improved, making CT imaging more popular in recent years. Koestel and Schlüter (2019) used CT scanning to assess soil structure and provided an Image J software plugin for semi-automated processing of three-dimensional X-ray soil images (Soil J), and this method shows great potential in quantifying soil structure dynamics related to the formation and degradation of individual structures under field conditions. Le Bayon et al. (2021) used X-ray micro-computed tomography to characterize the underground soil aggregates of different types of earthworms and found that there were significant differences in the volume ratio of mineral particles in soil pores according to the different types of earthworms. Tian et al. (2022) evaluated the changes of soil structure under different tillage managements by bulk density, anti-permeability, water retention curve, minimum water limit range and X-ray computed tomography, and studied the effects of long-term different tillage managements on the soil structure of silty soil. It is suggested that the minimum water limit range and the macropore morphological characteristics obtained by X-ray CT should be considered in the study of soil structure (Tian et al. 2022). Tian et al. (2023) explored whether no-tillage reduced the negative impact of harvest compaction on soil pore characteristics in Northeast China based on CT scan images. The results showed that no-tillage was more resistant to traffic than scraper ploughs that reduced soil porosity and permeability due to weak soil structure (Tian et al. 2023). CT scanning is a non-invasive and non-destructive technique, which can obtain the only image that characterizes the geometric and topological characteristics of soil without destroying the original soil pore structure. CT provides high-resolution images that capture the details of tiny pores and microstructures. The data generated by the CT scan can be used to construct a three-dimensional image, allowing researchers to visualize the pore structure inside the soil. This 3D view allows a comprehensive analysis of pore connectivity and spatial arrangement and provides valuable insights into how pores affect water movement, ventilation, and root growth. CT scan data can be quantitatively analysed, such as porosity, pore distribution and pore connectivity (Cheng et al. 2012a). However, its measurement cost is high and limited by the resolution of digital images. The higher the accuracy requirement is, the more expensive the

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price is. The minimum detectable aperture depends on the resolution of the scanner. Although CT can capture micron-sized pores, ultra-fine nano-sized pores may not be visible and other technologies are needed. There are some difficulties in describing the connectivity of individual soil pores. CT scans use X-ray radiation, which is risky for both the operator and the environment (Sun et al. 2015). The state of the soil sample, including its water content and density, affects the quality of the CT image. Wet or highly compacted soil may pose challenges. CT scanning requires a suitable size of soil samples to adapt to the scanner, so it is not suitable for large soil samples. CT scans cannot capture information in non-visible regions, such as roots and organic matter, and therefore may not provide a complete image of soil pore structure. The accuracy of soil pore structure obtained by CT scanning depends heavily on the resolution of CT images. It is recommended to use industrial CT and higher-precision electronic CT to ensure the accuracy of the analysis results. At present, scholars often use PVC pipes to collect field soil and transport it back for CT scanning, but transportation will have a serious impact on soil pores, especially macropores. It is recommended to use portable CT to scan the newly collected soil column immediately under conditions, so as to analyse soil pores more accurately. During transportation, soil samples should be kept wet after collection to prevent dry cracking and collapse, but excessive wetting should also be avoided.

RECENT STUDIES ON SOIL PORE

With the continuous development and improvement of CT technology, in recent years, scholars have combined this method to study soil pores. The type of CT has also gradually developed from X-ray CT (X-CT) to nuclear magnetic resonance CT (NMR-CT), positron CT (PET), ultrasonic CT (U-CT), etc. Especially around 2010, a microtomography scanner capable of scanning entire fragments with a diameter of 10 cm and a height of 15–20 cm at a resolution of about 10 μm appeared on the market, opening up new possibilities for studying soil pore structure at the microscopic level (Abrosimov et al. 2021).

The three-dimensional morphology of pores is quantified by software

With the development of science and technology, there are many three-dimensional image analysis software on the market, such as AVIZO 9.0, Image J, VG Studio MAX 2.2, Arc/Info 10.0, Paraview, etc., which greatly improves the efficiency of image processing. Through this image analysis software, not only the number of pores, equivalent pore diameter, surface area and volume can be obtained, but also the three-dimensional pore model reconstruction can be carried out to obtain pore tortuosity, connectivity, node density, network density, inclination angle, fractal dimension, path number and so on. However, the quantification and visualization of pores by software do not consider the irregularity and heterogeneity of pore structure. In addition, threshold segmentation and screening of pores based on human observation lead to low segmentation accuracy and inaccurate description of pore morphology. Therefore, it is mostly used for qualitative analysis, and errors will occur in quantitative analysis. The following picture is that we use the relevant image analysis software to extract the soil pore and three-dimensional reconstruction (Figure 1).

Using correlation functions to study soil structure and soil pore space

Usually, the ideal situation for describing the structure of an object should be mathematically represented by a function or a parameter of this function, and the opposite problem should be considered, that is, the structure is restored by a function, also known as reconstruction (Jiao et al. 2007). Although local porosity, pore size distribution, tortuosity, fractal dimension and node density can quantitatively characterize the connectivity of soil pores, these characteristics only describe different aspects of porous media structure. At present, it is not clear that the general descriptors of pore space and soil structure (quantitative indicators reflecting all necessary characteristics of pores) (Abrosimov et al. 2021). Gerke et al. (2012a) verified the possibility of describing and restoring pore space and soil structure from a two-point correlation function by simulated annealing (SA) method in 2012. The experimental results show that the reconstruction of massive soil with scattered circular pores based on pore morphological parameters is the most successful. In order to improve the accuracy of describing soil structure and pore space by function, it is also possible to use multi-point function or develop a method considering soil anisotropy in combination with other types of functions (Gerke et al. 2012a). On this basis, Gerke and Karsanina (2015) developed

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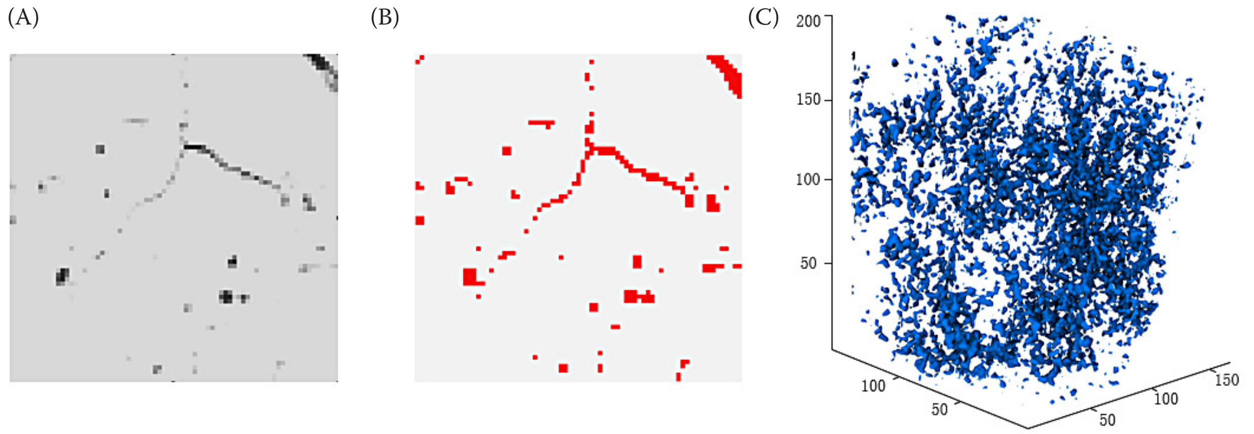

Figure 1. Three-dimensional reconstruction of soil pores under mulched drip irrigation using image analysis software: single soil slice obtained by CT scan (A), soil pore structure was extracted by Image J (B), three-dimensional reconstruction of soil pore structure (C)

a multi-scale image combination general stochastic method based on extensible correlation function in 2015 and demonstrated its effectiveness on the two-dimensional and three-dimensional structures of 27 spatial correlation functions. It is found that the appropriate weighting of the objective function achieves completely accurate reconstruction that cannot be achieved by traditional unweighted methods. This method can characterize and reconstruct any complex structure and contribute to solving the inverse problem of stochastic reconstruction (Gerke & Karsanina 2015). Karsanina et al. (2015) also applied two-point probability and linear correlation functions to characterize and reconstruct two-dimensional soil images and introduced cluster correlation functions to better characterize soil connectivity and compare the quality of reconstruction schemes. In addition, for the first time, the correlation function was calculated in four directions and applied to natural porous media (soil). Based on the two-point probability function and linear correlation function calculated from the original soil slice image, the two-dimensional soil structure was reconstructed by simulated annealing optimization technique. The future improvement of this new method will help overcome the current limitations in reconstructing soil structure (Karsanina et al. 2015). In 2020, the soil structure information in the form of 3D binary image was successfully compressed into a set of correlation functions (each function was described by six fitting parameters). Pores are calculated in three orthogonal directions using four different correlation functions (two-point probability, linearity, clustering, and surface-surface function). This method was applied to 16 different soil 3D images obtained by X-ray micro tomography and successfully segmented into pores and solids. It is proved that fitting the calculated correlation function and simplifying it into multiple parameters is an effective method to compress soil structure information. The ability of correlation functions to compress soil structure information is established, which is crucial for constructing multi-scale digital soil structure models of any complexity (Karsanina et al. 2020).

Studying soil pores with SEM and other techniques

With the widespread use of computed tomography in soil, scholars can describe soil structure on the micron scale, but this description is not enough to describe all the necessary processes or characteristics of soil. SEM is a large-scale precision instrument for high-resolution micro-regional analysis. It has the characteristics of large depth of field, high resolution, intuitive imaging, strong three-dimensional perception, and wide magnification range. It can be used to study nanoscale soil pores (Zhao et al. 2021). Studying soil pores in combination with SEM and other scientific technologies is a promising research direction in recent years. In 2020, Gerke et al. first applied focused ion beam scanning electron microscopy (FIB-SEM) imaging to soil. CT and FIB-SEM were performed on 50 μm^2 samples, respectively. It was found that FIB-SEM can provide more comprehensive information on the internal structure of soil at the nanoscale, and submicron pores with a pore size of 2.5–10 nm were observed in the cross section of SEM (Gerke et al. 2021). Figure 2 showes the steps

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of Gerke et al. (2021) studying nano-scale soil pores through FIB-SEM. Allegretta et al. (2022) studied soil aggregates using a combination of scanning electron microscopy and microanalysis (SEM-EDX), and used Datamuncher Gamma software to manage the SEM-EDX data cube, and finally successfully identified and segmented different phases in soil aggregates (silicate, aluminosilicate, calcium carbonate, calcium phosphate, organic matter, iron oxide). Compared with CT scanning technology, SEM can provide more microscopic and more comprehensive soil information. However, the reconstruction of porous three-dimensional microstructure from SEM image data has not been solved so far. It can only study a limited area. Pretreatment may cause soil damage, and the cost is high (including microscopes and milling tools). The operation is time-consuming and laborious (the sample needs to be pretreated and the operator needs to maintain long-term vigilance). Therefore, it is impossible to study a large number of soil samples by this method alone. It is necessary to combine other technologies to conduct optimal research on soil structure according to different conditions (Prill et al. 2013).

Using neural network to segment soil pore structures in images

Any method of analysing soil pores through images requires image segmentation. Previous studies often use threshold segmentation based on the subjective consciousness of researchers to transform the original image into a binary image (such as black represents pores and white represents soil), resulting in low segmentation accuracy and

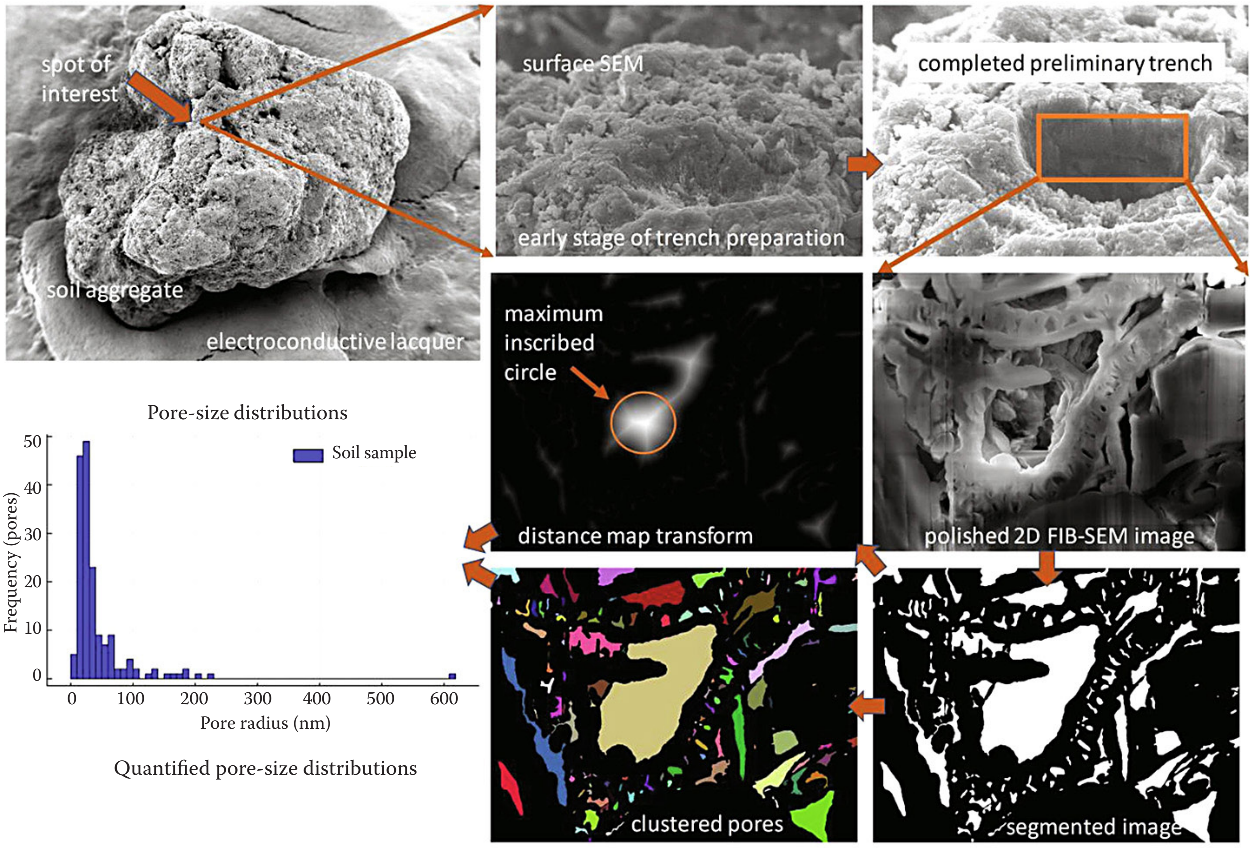

Figure 2. The general scheme of all the necessary steps to study soil structure at nano-scale including FIB-SEM imaging and the subsequent image processing; the arrows indicate the workflow starting from the location of the spot of interest for FIB milling and the following trench preparation; a 2D FIB-SEM image is obtained after polishing the back wall of the trench; image processing steps include image segmentation (binarization into pores and solids – shown in white and black, respectively), distance map transform and clustering procedures, which combination allowed for finding the maximum inscribed circle for each pore, and, finally, to quantify the pore-size distribution based on FIB-SEM image (Gerke et al. 2021)

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inaccurate description of pore morphology. Later, in order to make the binary segmentation results more accurate, some scholars tried local threshold method, global threshold method, regional growth method, etc., which improved the accuracy to a certain extent, but did not fundamentally change the defects of binary segmentation. In recent years, the use of convolutional neural networks for segmentation has become a hot spot in the study of soil pores (He et al. 2015; Han et al. 2021). Cortina-Januchs et al. (2011) proposed a method of integrating image processing, clustering technology and artificial neural network to classify pore space in soil images. Image processing is used for image feature extraction. Three clustering algorithms (K-means, fuzzy C-means and self-organizing map) are implemented to segment images. Artificial neural network is characterized by high modularity and flexibility, which is very effective for large-scale and general pattern recognition applications (Cortina-Januchs et al. 2011). Han et al. (2019) proposed a simplified convolutional network (SCN) to automatically identify solid and pore structures. The SCN can accurately identify irregular boundaries and complex structures from the complex layered structure of the soil, and screen soil pores under different physical conditions. In 2020, SCN was applied to the study of soil pore structure in the freeze-thaw alternation. The parallel thinning method was used to extract the soil macropore skeleton, and good experimental data and research results were obtained. They proposed a SCN to automatically identify the solid and pore structure, and used the SCN method to segment the pore structure. The experimental data show that the SCN method can accurately identify the pore structure of soil CT images under different physical conditions. In addition, the most advanced artificial intelligence technology is introduced into the soil field to provide intelligent technology for the soil micro-morphological tool set (Han et al. 2019, 2021). Figure 3 is a schematic diagram of soil pores extracted using a simplified convolutional neural network model. Lavrukhin et al. (2021) used convolutional neural network (CNN) to segment soil X-CT images, and used standard computer vision metrics and pore-scale simulations to evaluate the accuracy of segmentation to calculate the permeability of the generated 5D binary soil images, and discussed related improvement methods to build a more advanced network architecture. Figure 4 shows the workflow of VGG16 network model. Among all kinds of segmentation methods, threshold method, edge method and clustering method are easily affected by noise, and it is difficult to obtain the detailed information of pores, and there are over-segmentation and under-segmentation phenomena. Compared with other pore segmentation techniques, the use of neural networks to segment soil pores in images has high segmentation accuracy. By autonomously learning the characteristics of pore structure, the irregular pore structure can be effectively segmented, especially the detailed information of pores can be accurately depicted, which contributes to the true reduction of the geometric shape and spatial distribution of soil pores. Deep learning is applied late in the field of soil. It can effectively avoid noise interference and has good output results. However, it requires a large amount of sample data to do the training set, and its large sample dependence makes it limited in practical applications.

Establishing the model of soil physical properties based on the data of soil structure

According to the soil structure data, the corresponding physical properties model can be established,

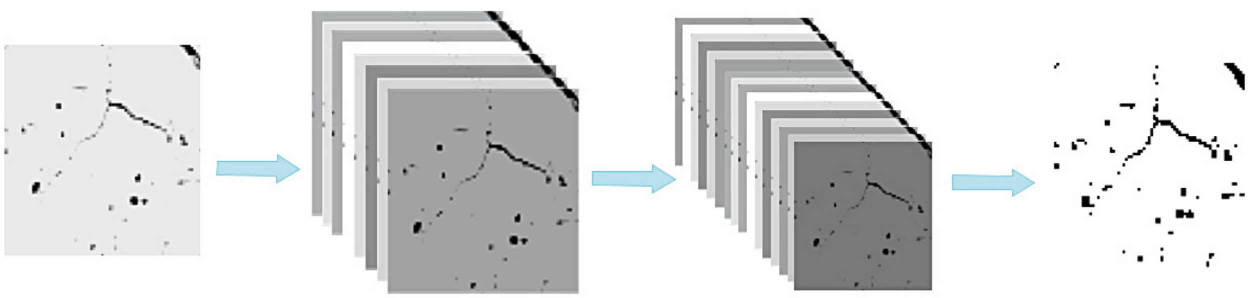

Figure 3. Using simplified convolutional neural network model to extract soil pore schematic diagram

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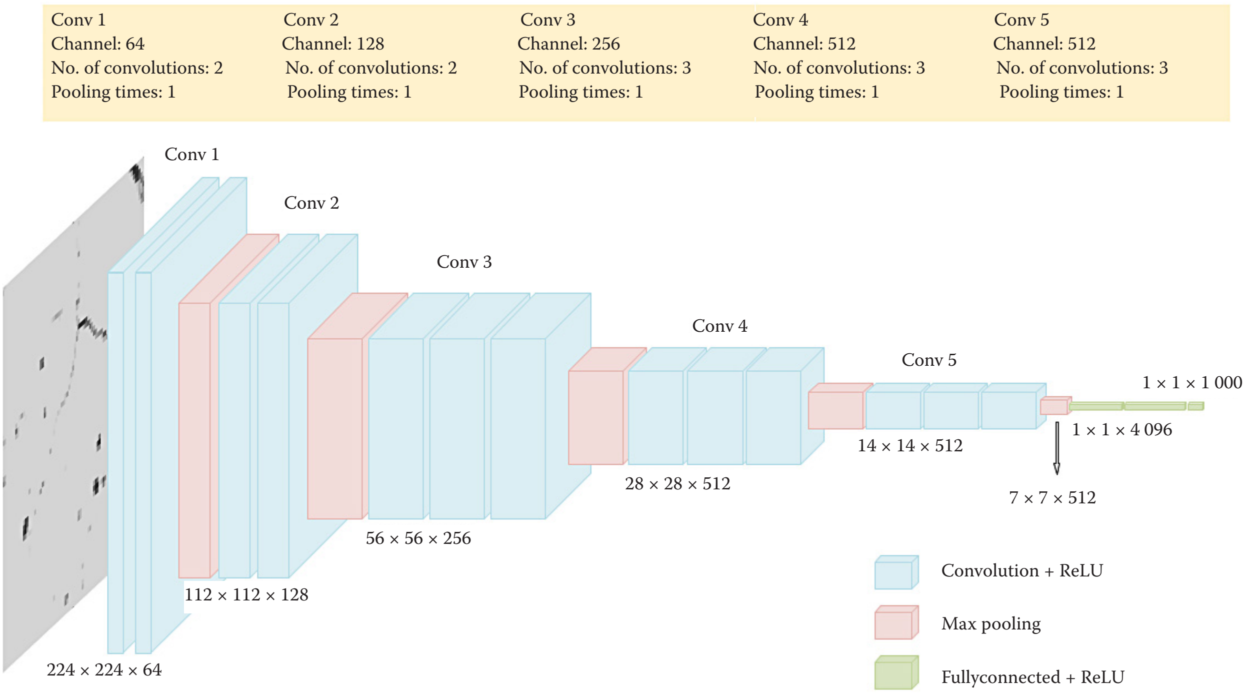

Figure 4. VGG 16 network model (a convolutional neural network) working diagram

which can be used to simulate physical properties, including hydraulic transmission. These techniques can be roughly divided into two categories: direct models and simplified algorithms. Direct methods include many, for example, (1) level set methods (Prodanović & Bryant 2006); (2) finite difference method (FDM) applied for the Laplace and Stokes equations (Gerke et al. 2012b); (3) fluid mechanics of smoothed particle (SPH) method (Holmes et al. 2016); (4) FEM, FVM and VoF (Bilger et al. 2017); (5) phase field or density functional method (Demianov et al. 2011; Rokhforouz & Akhlaghi Amiri 2017); (6) Lattice Boltzmann method (LBM) (Pot et al. 2020). However, these methods require a large amount of computing and storage capacity, and the simulation area is limited. Even if high-performance computing standards are used, it takes several weeks to complete the calculation of a small area. Therefore, more effective strategies for computer use include reducing the amount of information by simplifying the soil structure. It is of great significance to use the pore network model (PNM) to retain the significant connectivity and size characteristics of the pore space (Pot et al. 2022). Compared with pore-scale modelling methods (such as LBM and particle method), PNM has less calculation time. Its basic idea is to simplify the actually very complex pore space into an interconnected pore network system composed of pore bodies and pore throats. In soil and due to the inherent simplification of pore space in model construction, less computer capacity is required (Abrosimov et al. 2021). The computational requirements of pore network simulation are much lower than direct methods, which allows researchers to combine more heterogeneity when modelling larger rock volumes (Xiong et al. 2016). Through the analysis of CT images of soil slices, Liu et al. (2004) quantitatively obtained the distribution of soil pore size and connectivity parameters, established a related network model, simulated the process of soil water movement on the pore scale and predicted the hydraulic properties of near-saturated soil, but ignored the soil medium. It is composed of solid particles, pore space and fluid inside the pores, and treats the soil as a continuous medium (Liu et al. 2004). Vogel (2000) used PNM to simulate soil pore size, connectivity, water retention characteristics, permeability and soil solute transport. In 2017, Mehmani and Tchelepi (2017) determined the minimum requirements for predicting PNM of solute transport in micromodels and developed new PNM and network extraction methods. Gharedaghloo et al. (2018) developed a new code for PNM and applied it to peat soil by simulating advection and diffusion transport processes through

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a three-dimensional unstructured pore network. The pore network of peat soil was extracted from X-ray microtomography images, and it was confirmed that the hydraulic properties of peat soil were controlled by its pore size and pore tortuosity. Daneshian et al. (2021) also proposed a method to determine the relative hydraulic conductivity of unsaturated coarse-grained soil by constructing PNM only according to the soil water retention curve without complex imaging data. The results show that compared with other models, the accuracy of PNM is reasonable and the function is better. It can be used not only to determine the unsaturated hydraulic conductivity, but also to simulate the material migration in soil (Daneshian et al. 2021). The following is a soil pore structure model based on soil slices (Figure 5).

CONCLUSION

The research on soil pore structure in foreign countries can be traced back to the 1950s and 1960s, while China has only begun to study soil pores in recent years, and most of them infer the pore structure inside the soil by infiltration to obtain the water characteristic curve. There is a lack of research on pore formation mechanism and quantitative pore three-dimensional characteristics. In the future, research on pore size, distribution, connectivity and three-dimensional space should be strengthened.

At present, the existing soil pore research methods have their own advantages and disadvantages. It is necessary to constantly explore and innovate in the process of use, and find a research method suitable for their own experiments. CT scanning method and model fitting method are commonly used methods to study soil pores. Compared with other methods, although these two methods can obtain more accurate soil pore structure, they also have some disadvantages, which need to be continuously improved in use to improve the accuracy of soil pore structure.

In addition, this paper also summarizes the development trend and prospect of soil pore structure research:

(1) There is no same standard for the threshold and name of pore size classification at home and abroad. It is of great significance to establish a unified pore classification standard.

(2) At present, the research on soil structure is based on small samples, but the real soil space is complex and heterogeneous, so it is impossible to directly quantify the soil pores on the field scale. Therefore, how to expand the research results on the spatial scale is also a difficulty that needs to be overcome in the current research.

(3) There is no tomography camera directly used in soil research in the world. Most scholars use medical CT or industrial CT to scan soil samples. The invention of a special soil imaging instrument for soil structure research has far-reaching significance for future soil pore research.

(4) Using neural network to segment soil solids and pores in digital images is a leap-forward progress in studying soil based on digital images. If the im-

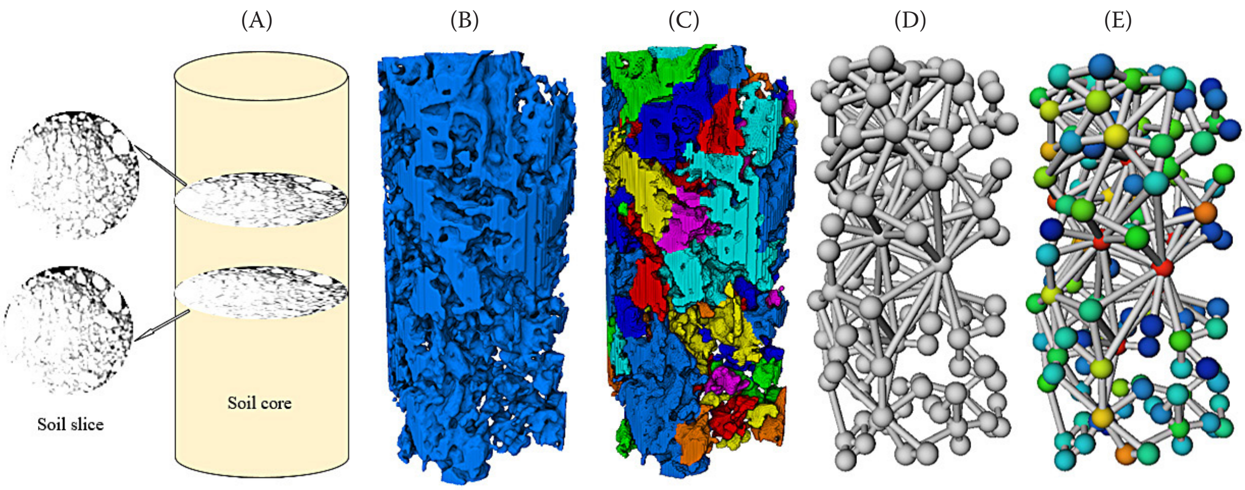

Figure 5. Establishment of soil pore structure model based on soil slices: undisturbed soil column (A), three-dimensional pore model established by Avizo (B), characterize different connected pores with different colours (C), connected pore network structure established after removing isolated pores (D), optimized pore network structure model (E)

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age automatic segmentation technology of neural network can be successfully developed or the intelligent image data segmentation service can be created, the pore structure characteristics can be analysed more quickly and accurately based on soil tomography data.

(5) Although the existing pore network models can intuitively simulate the physical and chemical processes on the pore scale and predict the hydraulic properties, they all simplify the soil pore structure to varying degrees. In the future, the model mechanism should be continuously improved to express the geometry and topology of soil pores more accurately.

(6) There are many open source programs for fault image data visualization and filtering in the market. Further development of these software and programs with more powerful modeling functions is conducive to further reconstruction and research of soil pore structure.

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Received: July 7, 2023
Accepted: November 14, 2023
Published online: January 3, 2024