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Review

# Effects of vegetation roots on the structure and hydraulic properties of soils: A perspective review

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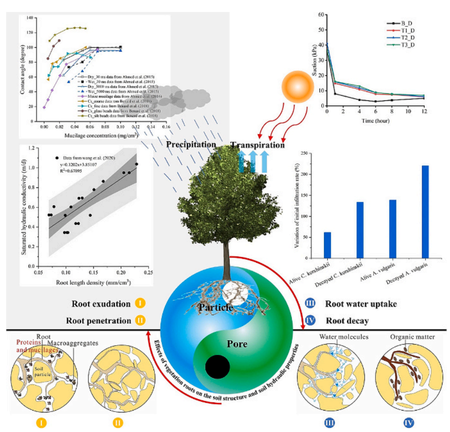
## HIGHLIGHTS

- Effects of vegetation roots on the structure and hydraulic properties of soils are reviewed.
- Mechanisms by which vegetation roots influence the soil structure and soil hydraulic properties are expounded.
- Relationships between soil hydraulic properties and vegetation root parameters are examined.
- Challenges remain in comprehending and quantifying the effects of vegetation roots on soil structure.

## GRAPHICAL ABSTRACT

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## ABSTRACT

This paper aims to provide a state-of-the-art review on the effects of vegetation roots on the soil structure and soil hydraulic properties. After a thorough review of current studies, the effects of vegetation roots are summarized into four: root exudation, root penetration, root water uptake and root decay. Root exudates alter the size and stability of aggregates, the contact angle of soil, and the viscosity and surface tension of pore fluid; root exudates of crops always increase the soil water retention capacity and decrease the soil saturated hydraulic conductivity. Root penetration creates new pores or clogs existing pores during root growth, and root parameters (e.g., root biomass density, root diameter and root length density) are well correlated to soil hydraulic properties. Root water uptake can apparently increase the soil water retention capacity by providing an additional negative pressure and induce micro-fissures and macropores in the rhizosphere soil. Root decay modifies the pore structure and water repellency of soil, resulting in the increase of soil macro-porosity, soil water retention, and the saturated hydraulic conductivity or steady infiltration rate. Some of the above four effects may be difficult to be distinguished, and most importantly each is highly time-dependent and influenced by a multitude of plant-

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related and soil-related factors. Therefore, it remains a significant challenge to comprehend and quantify the effects of vegetation roots on the soil structure and soil hydraulic properties. Unsolved questions and disputes that require further investigations in the future are summarized in this review.

## 1. Introduction

Soil is a critical component of the Earth, playing a vital role in various terrestrial processes such as the water cycle, carbon cycle, nitrogen cycle, and supporting life on this planet (see Fig. 1a, b) (Schimel, 2013; Fatichi et al., 2020; Maurel and Nacry, 2020). On the one hand, soil is the largest carbon source among terrestrial ecosystems, and can release substantial amounts of greenhouse gases (e.g., carbon dioxide, methane) into the atmosphere due to both human and microbial activities (Goldstein et al., 2022; Nottingham et al., 2020; Zhang et al., 2022). On the other hand, soil connects the atmospheric water, surface water and groundwater through precipitation and evapotranspiration, approximately 40 % - 60 % of the land precipitation is returned to the atmosphere via the soil-plant system (Oki and Kanae, 2006; Katul et al., 2012; Fatichi et al., 2016). Therefore, it is not surprising that soil plays an important role in the carbon cycle (or neutrality), water cycle and global climate change on the Earth. The soil properties are important factors that can shape the surface energy and surface evaporation of the Earth, regional climate, heat, vapor, and water fluxes (Betts et al., 2013; Vick et al., 2016; Fatichi et al., 2020; Tang et al., 2021; Novick et al., 2022). The soil hydraulic properties govern the infiltration, movement and redistribution of water in the soil, thereby affecting the interactions between surface water and groundwater, and are essential for establishing hydrological models at various scales (see Fig. 1) (Seneviratne et al., 2010; Livneh et al., 2015; Wang et al., 2020a; Novick et al., 2022). For these reasons, the soil hydraulic properties are of great significance in a variety of engineering applications, including the computation and resolution of infiltration-related geotechnical problems, analysis and mitigation of rainfall-induced geohazards (such as debris flow and landslides), as well as in agricultural management, ecological restoration and environmental protection practices (Lake et al., 2003; Wang et al., 2020b; Ng et al., 2022; Vereecken et al., 2022). However, the soil properties, including hydraulic properties, are suggested to be controlled by the soil structure, which is typically characterized by the

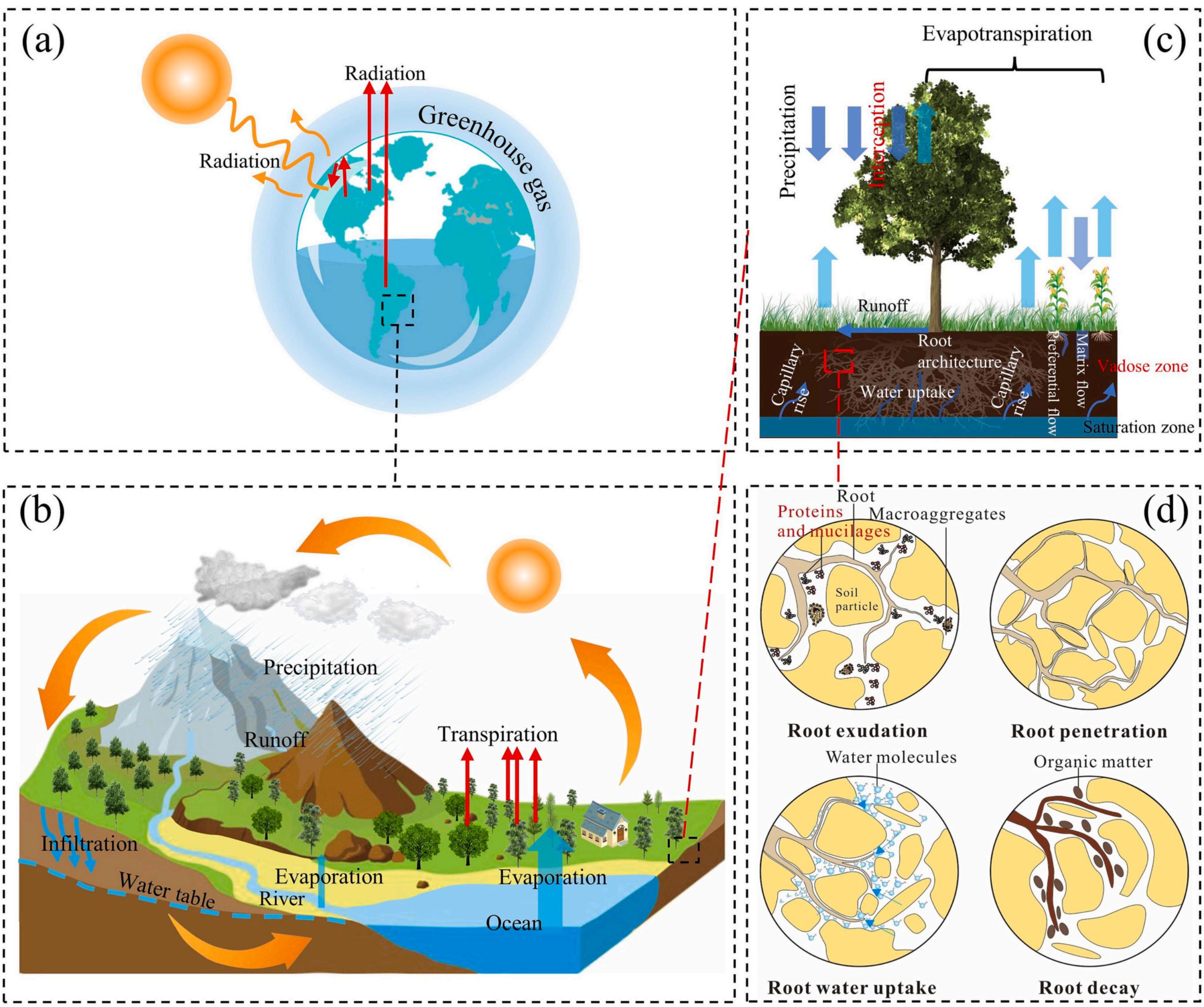


**Fig. 1.** The soil hydrological system and soil-plant-microbial-atmosphere interaction.

aggregate size, bulk density, grain-size distribution (GSD), pore-size distribution (PSD) and so on (Li et al., 2019; Rabot et al., 2018; Fatichi et al., 2020).

The soil structure and soil hydraulic properties are influenced by many factors, including the soil physical properties (e.g., mineral composition, GSD, organic matter content, moisture content, dry density, etc.) (Dexter et al., 2008; Li et al., 2016; Xiao et al., 2022a; Xiao et al., 2022b; Li et al., 2023) and environmental factors (e.g., temperature, freezing-thawing cycles, wetting-drying cycles, vegetation cover, human activities, etc.) (Chahine, 1992; Rabot et al., 2018; Chen et al., 2021; Fei et al., 2021a). Among these factors, vegetation, an important component of the Earth's surface, also plays a significant role in the water cycle, carbon cycle, and climate change. Moreover, vegetation restoration, as a technology for negative carbon emissions, has the potential to mitigate greenhouse gas emissions and extreme climate events (e.g., extreme drought and extreme rainfall) (Löbmann et al., 2020; Wang et al., 2021; Ng et al., 2022). As a result, it exerts a profound influence on the occurrence and prevention of some geohazards (such as shallow landslides, slope failure and soil erosion) (Stokes et al., 2009; Kim et al., 2017; Gonzalez-Ollauri and Mickovski, 2017; Löbmann et al., 2020; Baets et al., 2020; Fan et al., 2022). In general, vegetation roots can modify the soil structure and soil hydraulic properties through root exudation, root penetration, root water uptake, and root decay, according to current research (see Fig. 1c, d) (Lu et al., 2020; Shi et al., 2021; Ng et al., 2022). These four root effects have been extensively investigated by researchers from different fields, and their findings have been reviewed recently by several scholars (e.g., Lu et al., 2020; Shi et al., 2021; Ng et al., 2022). However, they placed greater emphasis on the consequence, namely changes in the soil hydraulic properties induced by vegetation roots; despite mentioning all known mechanisms, a comprehensive understanding of how vegetation roots modify the soil structure and hydraulic properties is still lacking. In addition, the reviews by Lu et al. (2020) and Shi et al. (2021) focused on the root-induced modification (RIM) of soil hydraulic properties, considering the soil (pore) structure as one of its influencing factors; however, any change in the size of aggregates, composition of solid or fluid materials in the soil can also lead to alterations in the soil properties (Carminati et al., 2016; Naveed et al., 2019; Ying et al., 2023; Xu et al., 2023). The hydraulic properties of soil are controlled by its structure; it is thus equally important to elaborate the impact of vegetation roots on the soil structure. Therefore, the full disclosure of the mechanisms by which vegetation roots modify the soil structure and soil hydraulic properties through processes such as root exudation, root penetration, root water uptake, and root decay is imperative.

In this review, we focus on the mechanisms by which vegetation roots impact the soil properties. Current research on the four main root effects namely, root exudation, root penetration, root water uptake and root decay on the soil structure and soil hydraulic properties will be summarized and discussed at first. Then, changes in the soil structure and soil hydraulic properties as a result of the above four processes will be presented and analyzed, and connections between the soil structure, soil hydraulic properties, and parameters associated with vegetation roots will be established based on the data from the literature. Finally, unsolved problems and directions for future research, and potentially useful methods and techniques will be provided.

## 2. Soil structure and soil hydraulic properties

In the literature, the soil structure is generally referred to the size, shape, arrangement and connection of particles or aggregates (Fao, 2006; Schoeneberger et al., 2012; Bottinelli et al., 2015; Li et al., 2016; Rabot et al., 2018; Fei et al., 2021b). The size, orientation, and fractal characteristics of pores were also used to characterize the soil structure in some studies (Xiao et al., 2022a; Xiao et al., 2022b; Yu et al., 2022; Li et al., 2023). From the solid phase perspective, over long timescales, the production of primary mineral particles in the soil is mainly controlled by climate conditions. The parent materials transform into primary particles through daily and seasonal freezing-thawing and wetting-drying cycles over millennia. Then, primary particles and domains (grouped parallel clay plates) form organic-mineral complexes (<0.02 mm diameter), microaggregates (0.02–0.25 mm diameter) and macroaggregates (>0.25 mm diameter) under the actions of various binding agents or forces (e.g., van der Waal's attraction, coulombic attraction), according to the model of aggregation proposed by Tisdall and Oades (1982). In a soil where organic matter is the main binding agent, organic binding agents have been classified into (a) transient, mainly polysaccharides, (b) temporary, roots and fungal hyphae, (c) persistent, resistant aromatic components associated with polyvalent metal cations, and strongly sorbed polymers (Tisdall and Oades, 1982; Rabot et al., 2018; Vereecken et al., 2022). In the end, aggregates with different sizes and large primary particles form the skeleton of the soil structure.

From the pore perspective, pores exist both inside and between aggregates in the soil. Similar to particles or aggregates, pores also have their size, shape, orientation, tortuosity, fractal characteristics and spatial arrangement. According to the pore size, pores were divided into three groups (micropores, mesopores, and macropores) (e.g., Ying et al., 2023; Xu et al., 2023) or four groups (small, medium, large and giant pores) (e.g., Xiao et al., 2022b; Li et al., 2023). For instance, the pores in loess soils were divided into macropores, spaced pores, intergranular pores, and intragranular pores according to their size relative to surrounding aggregates or particles to facilitate the interpretation of wetting-induced collapse (Gao, 1981; Dijkstra et al., 1995; Derbyshire, 2001). Lei (1988) classified the pores in loess soils into original pores (inter-aggregate pores and intra-aggregate pores) and secondary pores (root holes, wormholes, cracks, fissures, etc.). Moreover, most soil and environmental scientists held that the pores formed due to arrangement of primary particles and aggregates should be termed textural pores, and the large pores due to biological activity, climate change and human activity should be termed structural pores (Almajmaie et al., 2017; Rabot et al., 2018). Pores in the soil contribute to the water infiltration and movement, soil water retention, and soil deformation (Fredlund and Xing, 1994; Vanapalli et al., 1996; Vereecken et al., 2022). For this reason, the soil structure is believed to be a key parameter that should be considered in constitutive models related to the Earth system and terrestrial ecosystem (Zhang and Schaap, 2019; Fatichi et al., 2020; Vereecken et al., 2022; Sullivan et al., 2022). However, due to the difficulty in the parameterization of soil structure, few studies have tried to integrate the soil structure into these models.

The soil hydraulic properties mainly concerned in this review include the saturated hydraulic conductivity ($K_s$), unsaturated hydraulic conductivity, and soil water retention curve (i.e., relationship between volumetric water content and suction, SWRC). The soil hydraulic properties are key parameters that control the water infiltration and movement in the soil. They are required for the development of hydrological models of various scales and resolution of natural resource problems (Fatichi et al., 2020; Lu et al., 2020; Taylor et al., 2012; Maxwell and Kollet, 2008). Early efforts were mainly made to the development of SWRC models over the entire suction range (e.g., Gardner, 1958; Brooks and Corey, 1964; van Genuchten, 1980; Kosugi, 1994; Fredlund and Xing, 1994; etc.). Additionally, various pedotransfer functions (PTFs) have been proposed to predict the SWRC from readily accessible soil properties (e.g., dry density, void ratio, GSD, PSD, etc.) (Gallipoli et al., 2003; Vereecken et al., 2010; Hu et al., 2013; Zhang and Schaap, 2019; Wang et al., 2022). These PTFs related the parameters in the well-known SWRC models, such as the van Genuchten model and Fredlund-Xing model, to soil properties, based on the regression analysis of a dataset (comprising soils with similar or different structures and mineral compositions). Li et al. (2018) provided a brief summary of such PTFs.

The hydraulic conductivity for a saturated soil (i.e., saturated hydraulic conductivity) is generally assumed to be constant (Li et al., 2023). However, it can vary by several orders of magnitudes for an unsaturated soil (i.e., unsaturated hydraulic conductivity). As the soil desaturates, its hydraulic conductivity decreases not only because there is less cross-sectional area through which water can flow, but also due to an increase in the tortuosity of the flow path in the soil. As a consequence, an arithmetic decrease in the volume of water generally results in a logarithmic decrease in the hydraulic conductivity (Mualem, 1976; van Genuchten, 1980; Fredlund et al., 2012). The van Genuchten - Mualem model, which combines the van Genuchten SWRC equation with the Mualem relative hydraulic conductivity equation, is widely recognized as the most commonly used model for unsaturated hydraulic conductivity. Afterwards, a lot of work has been done to develop empirical relationships (i.e., PTFs) between the model parameters and soil properties (e.g., soil organic matter, dry density, GSD, PSD, initial water content) or environmental factors (e.g., wetting-drying history, freezing-thawing history, stress history, and vegetation) that can be easily obtained in the field or laboratory. PTFs are empirical in nature, which inspired many researchers to develop site-specific PTFs of various scales (Vereecken et al., 2010; Patil and Singh, 2016; Wang et al., 2017; Zhang and Schaap, 2019). However, PTFs do improve the efficiency of obtaining the soil hydraulic properties (Vereecken et al., 2010; Zhang and Schaap, 2019). And with the emergence of artificial intelligence and increasingly comprehensive soil databases, the accuracy of PTFs will increase, and PTFs will definitely be warmly welcomed in future regional-scale hydrological investigations (Lu et al., 2020; Vereecken et al., 2022; Wang et al., 2022).

## 3. Effects of root exudation on the soil structure and soil hydraulic properties

Root exudates are a suite of substances secreted by roots of living plants in the rhizosphere. They are always composed of organic compounds such as organic acid (e.g., macromolecular polysaccharides), amino acid and amide, enzymes, growth factor, phenolic acid, coumarin, sugar, and others (see the central circle in Fig. 2). The chemical composition of root exudates is influenced by many factors, including plant species, plant age, soil type, soil water content, pH, temperature, etc. (Czarnes et al., 2000; Naveed et al., 2017; Naveed et al., 2018; Zhong et al., 2021; Chai and Schachtman, 2022). It is worth noting that a matrix of insoluble high-molecular-weight compounds in root exudates (e.g., polysaccharides, proteins, carbohydrates, organic acids, etc.) is termed mucilage (see Fig. 2) (Traoré et al., 2000; Ahmed et al., 2015; Zhong et al., 2021; Zhang et al., 2021a). Previous research demonstrated that the soil properties can be changed by root mucilage, including the soil structure (e.g., soil aggregation and pores), soil water retention capacity, water infiltration rate, etc., and different mucilages have different effects (Traoré et al., 2000; Czarnes et al., 2000; Ahmed et al., 2015; Carminati, 2013).

As stated before, aggregates are fundamental elements in the soil structure. Aggregates are associations of primary particles under the actions of various forces and bonding agents (e.g., colloidal material, oxides, calcium carbonate, and organic binding agents) (Six et al., 2004; Abiven et al., 2009; Weil and Brady, 2017; Araya and Ghezzehei, 2019). Root mucilage, a gel, is widely recognized as a bonding agent (Traoré et al., 2000; Czarnes et al., 2000; Erktan et al., 2017; Zhang et al., 2021a). Thus, root mucilage can change the soil structure by affecting the aggregate stability, size of aggregates or pores, and contact relation of soil particles (Read et al., 2003; Carminati et al., 2010; Galloway et al., 2018; Zhang et al., 2021a). The interaction between the soil structure and root mucilage has attracted wide attention, and the effects of root mucilage on the soil structure could be divided into two types (i.e., direct effect and indirect effect).

**Direct effect** Root mucilage can function as a stabilizing agent that enhances the physical bonding energy between soil particles, thus improving the aggregate/soil stability (see Fig. 2a). Traoré et al. (2000)

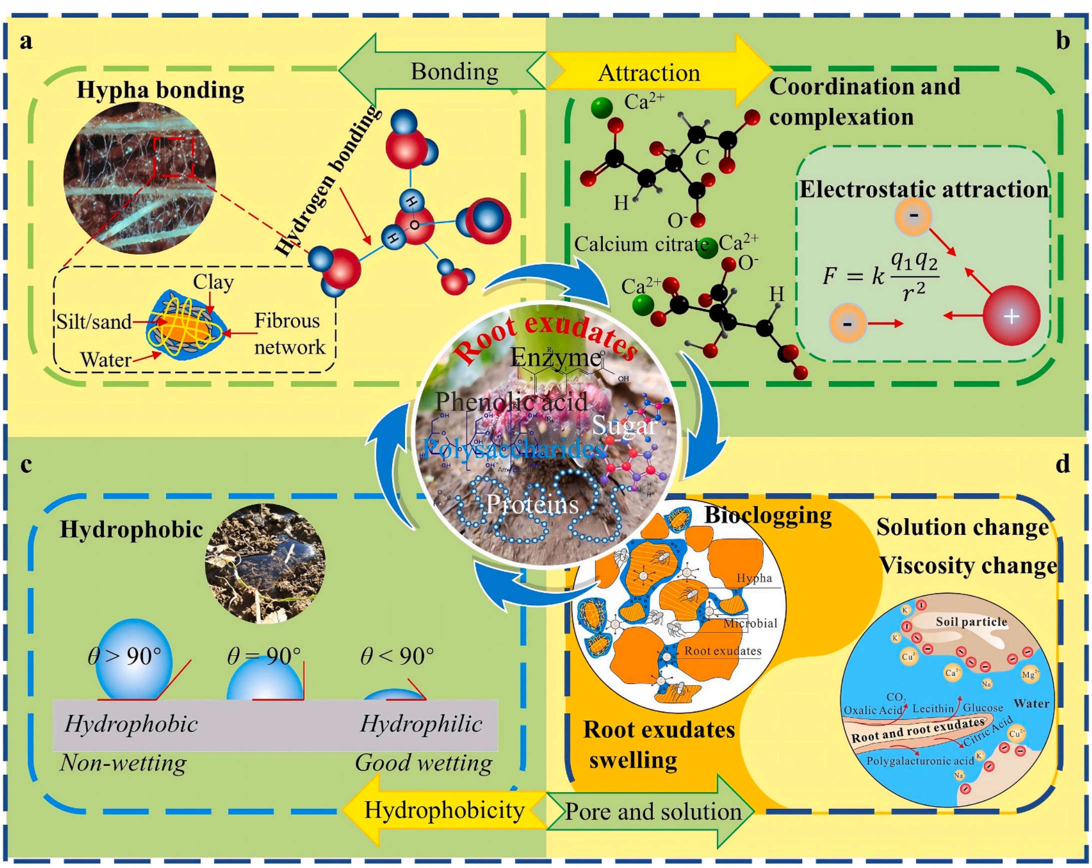


**Fig. 2.** Mechanisms underlying the impacts of root exudates on the soil structure and soil hydraulic properties.

compared the aggregate stability of the same soils amended with glucose, polygalacturonic acid, modelled soluble exudates and maize root mucilage, respectively. Their results showed that compared to the plain soil, the percentage of aggregates larger than 1 mm was increased; the aggregate stability of the soils treated with glucose, polygalacturonic acid, modelled soluble exudates and maize root mucilage was improved, while the stabilizing effect decreased with the curing time (may be due to the decomposition of mucilage, as per Carminati (2013)). They concluded that root exudates altered the soil structure by holding or sticking soil particles together to form macroaggregates. The study carried out by Czarnes et al. (2000) showed that xanthan and polygalacturonic acid can increase the bonding energy between soil particles, thereby protecting soil from deformation induced by wetting-drying cycles (i.e., cracks). They found that root exudates can stabilize the soil structure by forming a fibrous network to wrap or constrain soil particles (see Fig. 2a). Galloway et al. (2018) found that xyloglucan can effectively stabilize soil aggregates, and the weight proportion of aggregates with the size larger than 0.25 mm increases remarkably. Moreover, there were studies indicated that root exudates, as organic materials, carried a large number of negative charges on their surfaces, which can promote the formation of organic-mineral complex or mineral-associated organic matter (MAOM) in the soil and enhance the aggregate stability (see Fig. 2) (Tisdall and Oades, 1982; Abiven et al., 2009). Recent research also presented that the low-molecular-weight compounds (e.g., organic acid with carboxylic acid groups) in root exudates may draw minerals immediately and then form MAOM (Jilling et al., 2021; Fossum et al., 2022; Chari and Taylor, 2022). However, Erktan et al. (2017) examined the effects of some components of root exudates (i.e., tannins, protein, bovine serum albumin, polygalacturonic acid, tannins + protein, tannins + bovine serum albumin, and tannins + polygalacturonic acid) on the soil aggregate stability. Their results showed that the soil aggregate stability was hardly improved by tannins, and tannins increased the stabilizing effect of bovine serum albumin while decreasing the stabilizing effect of polygalacturonic acid. That is to say, tannins may inhibit the gelation process of certain components of root exudates. Meanwhile, that means not all components of root exudates have a positive effect on the soil aggregate stability.

**Indirect effect** Some researchers suggested that root exudates can shape the microbial community and increase the microbial activity, resulting in more microbial debris and hypha that are typically binding agents and dominate the formation of macroaggregates (see Fig. 2a) (Chai and Schachtman, 2022; Tisdall et al., 2012; Dennis et al., 2010; Moreno-Espíndola et al., 2007; Degens et al., 1996). Gao et al. (2017) suggested that the species and number of bacteria have a significant influence on the soil structure and strength. Zhang et al. (2021a) showed that hyphae grew remarkably on the fourth and fifth day in the sand amended with synthetic root exudates, while hyphae were hardly seen in the water-treated sand. They found that the sand amended with synthetic root exudates had a higher resistance to water infiltration than the water-treated sand, that is because the arrangement of particles was closer in the former soil. Researchers also found that some root exudates or organic matter can increase the soil hydrophobicity and thus maintain the stability of soil aggregates (Czarnes et al., 2000; Cosentino et al., 2006; Carminati, 2013; Carminati et al., 2016; Erktan et al., 2017). Experimental evidence has shown that root exudates can increase the contact angle of soil particles (see Fig. 3) (Ahmed et al., 2015; Ahmed et al., 2016; Benard et al., 2018; Naveed et al., 2019). It can be seen from Fig. 3 that the contact angle increases with the increase of root mucilage concentration, and the soil becomes hydrophobic when the mucilage concentration is higher than a certain value (i.e., the contact angle is larger than 90°). Moreover, note that the effect of root exudates on the contact angle of soil is also influenced by the environmental humility, soil particle size, and composition of root exudates (Ahmed et al., 2015; Ahmed et al., 2016; Benard et al., 2018; Naveed et al., 2019).

In summary, the mechanisms by which root exudates affect the soil structure and aggregate stability include: (1) to increase the bonding energy between soil particles (cement or wrap soil particles); (2) to promote the formation of MAOM (combine with soil particles mainly under cationic bridging and electrostatic attraction); (3) to protect aggregates from disintegration due to water infiltration or ponding (increase the hydrophobicity of soil particles or aggregates). All of these mechanisms are summarized in Fig. 2.

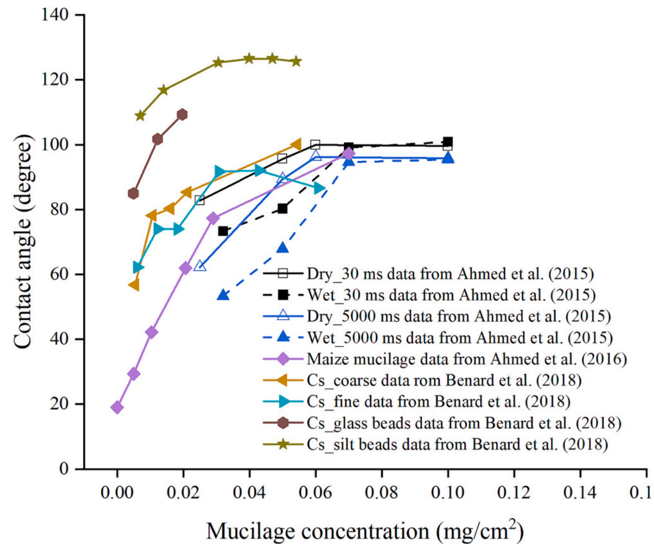


**Fig. 3.** The contact angle of soils amended with root mucilages of different concentrations (Note that "dry" or "wet" means the mucilage was collected from maize in dry or wet soil; "30 ms" or "5000 ms" denotes 30 ms or 5000 ms that was elapsed since the beginning of contact angle measurement; "Cs" means chia seed mucilage; "coarse, fine, silt, glass" denotes coarse sand (particle size: 0.5–0.63 mm), fine sand (particle size: 0.125–0.2 mm), silt sand (particle size: 0.036–0.063 mm) and glass (particle size: 0.1–0.2 mm), respectively).

Root exudates can thus affect the soil hydraulic properties (Carminati et al., 2010; Deng et al., 2015; Carminati et al., 2016). Currently, there are two views on the effect of root exudates on the soil water retention capacity. The mainstream view is that root exudates can increase the soil water retention capacity. For instance, Kroener et al. (2014) found that the application of chia seed mucilage (its chemical composition is similar to that of maize root mucilage) can enhance the water retention capacity of sandy loam. Their results were in line with the observation of Ahmed et al. (2014), who carried out experiments on a sandy soil that was amended with chia seed mucilage. Similarly, Naveed et al. (2019) reported that chia seed mucilage and maize root mucilage were capable of increasing the soil water retention capacity and hysteresis index (see Fig. 4a-c). The relative change rates of the SWRC parameters with respect to different mucilages and concentrations are presented in Fig. 4h. It is shown that the parameter $\alpha$ increases in response to the addition of root mucilage, except for ones with barley mucilage at a concentration of 4.6 mg/g. Under the concentration of 0.46 mg/g, the parameter $n$ reduces with the mucilage addition; while the opposite is true under the concentration of 4.6 mg/g. In addition, Deng et al. (2015) compared the water retention capacity of a sandy clay loam and that of the same soil amended with shepherd's purse seed mucilage. Their results showed that the addition of 0.5 % and 1 % (g/g) mucilage can make sandy clay loam hold more water (i.e., water content increases were up to approximately 6 % and 10 % (g/g)). These studies demonstrate that the physiochemical properties of root exudates play a dominant role in affecting the soil water retention capacity (Deng et al., 2015; Carminati et al., 2016; Naveed et al., 2019; Zhang et al., 2021a; Zhang et al., 2021b). These physiochemical properties include the water-absorbing capacity of exudates (i.e., root exudates can form polymeric gels that can absorb large volumes of water), the viscosity of root exudates, the surface tension of root exudates, and most importantly the composition of root exudates.

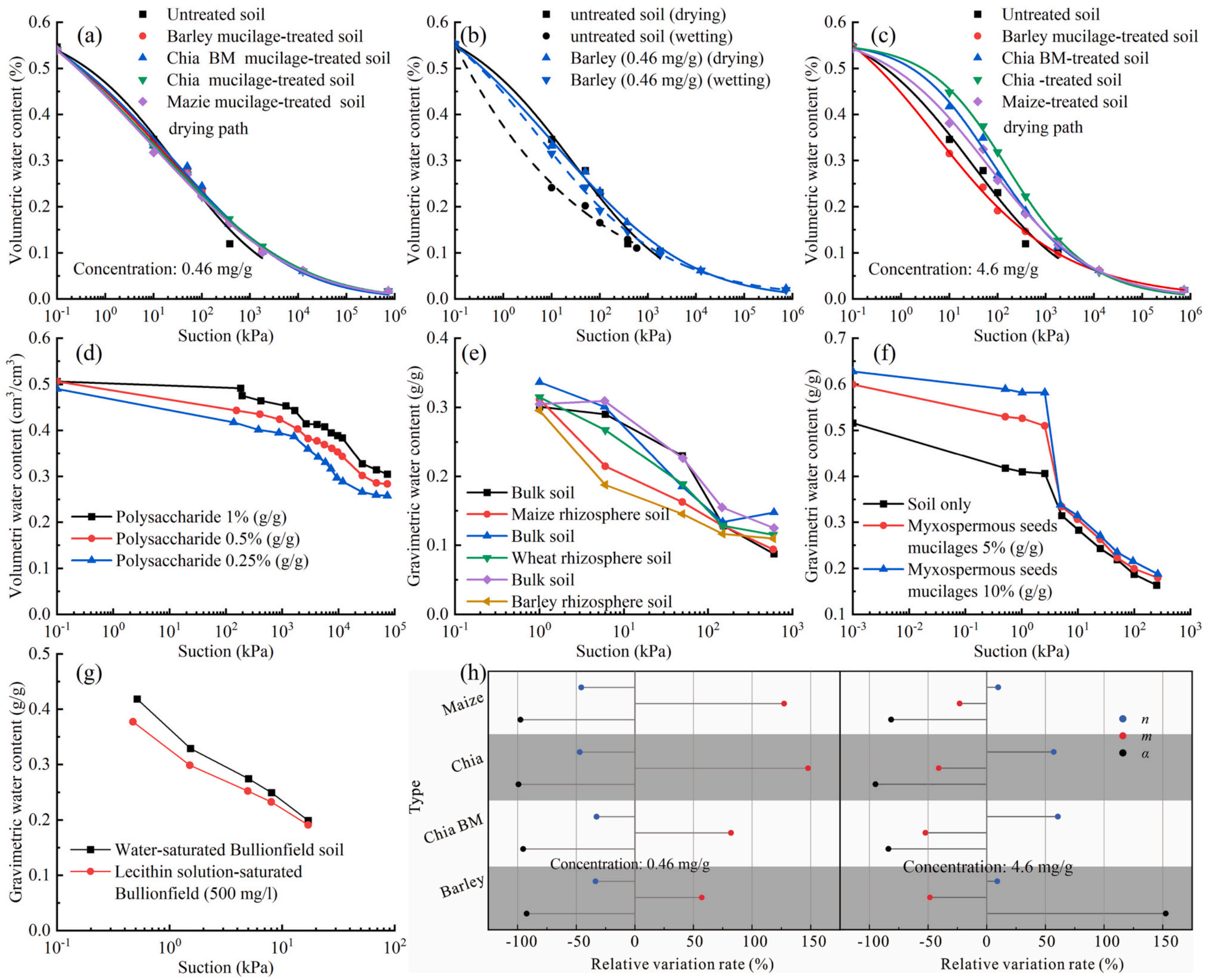


**Fig. 4.** SWRCs of root mucilage-treated soils: (a-c, h) data from Naveed et al. (2019); (d) Zhang et al. (2021b); (e) Whalley et al. (2005); (f) Deng et al. (2015); (g) Read et al. (2003). The relative variation rate was defined as (the parameter of mucilage-treated soil - the parameter of untreated soil)/the parameter of untreated soil.

Although most studies suggested that root exudates can enhance the soil water retention capacity, a few studies presented opposite results (e.g., Read et al., 2003; Whalley et al., 2005; Kroener et al., 2014). Read et al. (2003) measured the SWRCs of Bullionfield soil samples saturated with pure water and 500 mg/l lecithin solution by using the tension table method. They found that the water retention capacity of lecithin solution saturated-Bullionfied soil was remarkably lower than that of pure water saturated-Bullionfied soil (see Fig. 4g); they attributed this to the reduction of surface tension of pore fluid due to phospholipids. Whalley et al. (2005) reported that the soils collected from the rhizosphere of wheat, barley and maize tended to be drier than bulk soil at some studied suctions (see Fig. 4e). That is probably because, on the one hand, the low surface tension of mucilage reduces the water retention in the rhizosphere; on the other hand, the soils might be collected immediately after a rainfall since mucilage can turn hydrophobic upon drying (i.e., after a period of drying, mucilage rehydrates at a lower rate than bulk soil, the rhizosphere is thus drier than bulk soil, which is actually a self-protection root strategy according to Carminati (2013)).

Owing to that the composition and amount of root exudates vary with many factors, such as plant species, atmospheric environment and soil environment (keep in mind that mucilage is secreted to favor water availability to roots during drought), and the methods of cultivating and extracting root exudates are cumbersome and time-consuming, there has been relatively limited research conducted, and synthetic root exudates and analogs of the rhizosphere soil (soil amended with root exudates) were used in most related studies. Furthermore, the dynamic change effect of root exudates with environmental factors is rarely examined.

The effect of root exudates on the soil saturated hydraulic conductivity was rarely investigated. Kroener et al. (2014) and Kroener et al. (2018) studied the saturated hydraulic conductivity of chia seed mucilage-treated sandy soil and the results are summarized in Fig. 5. It is shown that the soil saturated hydraulic conductivity decreases by >1–3 orders of magnitude with the increase of mucilage concentration (see Fig. 5a). Moreover, they suggested that the effect of mucilage was dependent on the size of soil particles or aggregates, the larger the particle size was, the more significantly the soil saturated hydraulic conductivity varied with the mucilage concentration (see Fig. 5b). Deng et al. (2015) found that the addition of myxospermous seed mucilage at a concentration of 5 % (g/g) slightly reduced the permeability of sandy loam, resulting in a decrease in the saturated hydraulic conductivity from 0.12 to 0.18 m/d to 0.03–0.12 m/d; when the mucilage concentration increased to 10 % (g/g), the saturated hydraulic conductivity of sandy loam was generally <0.03 m/d. The addition of root exudates was found to increase the viscosity of pore fluid in the soil (Read et al., 2003; Bengough, 2012; Naveed et al., 2019), thereby reducing the saturated

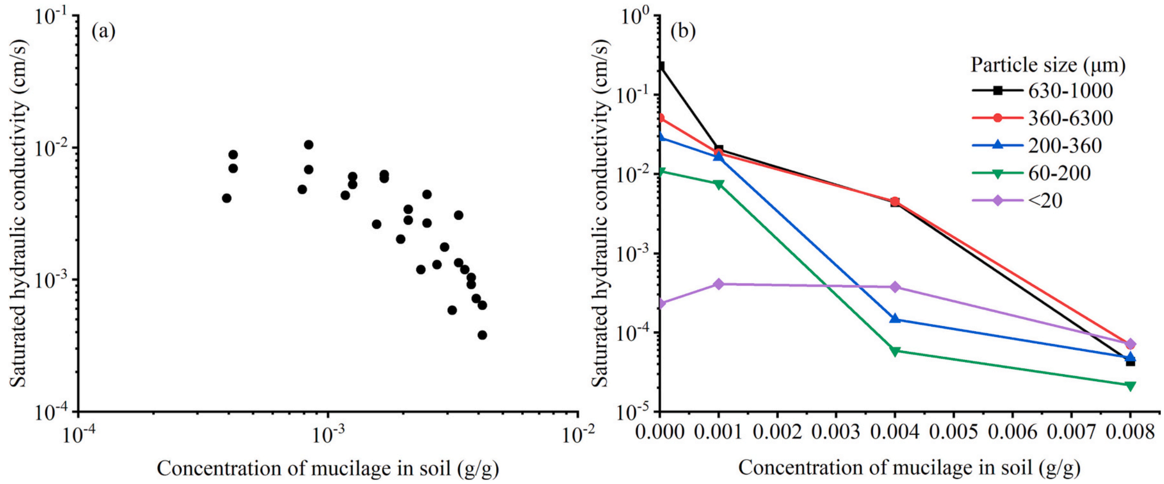


**Fig. 5.** Saturated hydraulic conductivities of mucilage-treated sandy soils: (a) data from Kroener et al. (2014) and (b) data from Kroener et al. (2018).

permeability coefficient. Some scholars also attributed the decrease in soil saturated permeability coefficient to the increase in soil density (Carminati et al., 2010; Kroener et al., 2014; Deng et al., 2015). Furthermore, some scholars suggested that this may be due to the pore structure change caused by the water absorption and swelling of root exudates (McCully and Boyer, 1997; Peng et al., 2011; Carminati, 2013; Carminati et al., 2016). For example, McCully and Boyer (1997) found that maize root mucilage has strong water-absorbing ability (mucilage can absorb water as much as hundreds of times its dry weight). While others suggested that the addition of root exudates may accelerate the microbial reproduction and metabolism, leading to clogging of soil pores (bioclogging) and ultimately a reduction in the saturated hydraulic conductivity (see Fig. 2d) (Thullner et al., 2004; Boult et al., 2008). In contrast, an interesting study conducted by Zhang et al. (2021a) recently showed that the addition of synthetic root exudates did not reduce the saturated hydraulic conductivity of sandy soil. They interpreted that root exudates could enhance the microbial activity, which might promote the formation of preferential channels and subsequently increase the water infiltration in the soil. Therefore, root exudates do not always decrease the soil saturated hydraulic conductivity based on these studies. In summary, the effect of root exudates on the soil saturated hydraulic conductivity could be interpreted from three perspectives: the swelling property of root exudates, the effect of root exudates on the soil pore structure, and the effect on the soil microorganisms. Further research is necessary to establish the correlation between curing time, microbial biomass, and saturated hydraulic conductivity of soil amended with root exudates.

## 4. Effects of root penetration on the soil structure and soil hydraulic properties

It is well known that plant roots are capable of modifying the soil structure to accommodate plant growth. As a result, plant roots can be thought of as architects for soils' “pore-clogging” and “pore-forming” at different growth stages. A considerable body of research has demonstrated that growing roots can exert pressure on surrounding soil particles or aggregates (Colombi et al., 2018; Zhu et al., 2019; Chen et al., 2022; Leung et al., 2023). For a growing plant root, the maximum pressure was estimated to be up to 1 MPa (Bengough et al., 2006; Oleghe et al., 2017; Chen et al., 2022). And once the penetration resistance of soil is greater than that pressure, plant grows slowly or even stops growing (Misra et al., 1986). In this regard, the growth of roots undoubtedly leads to a reduction in the porosity or void ratio of the rhizosphere soil (Dexter, 1987; Mooney et al., 2012). Moreover, Jin et al. (2017) discussed the effect of root penetration or growth on the soil anisotropy and summarized how roots exploit and occupy pores during growth. In a word, root penetration can alter the soil structure and soil hydraulic properties to accommodate the plant growth.

For the soil structure, root penetration mainly affects the size of aggregates, the connectivity or size of pores by producing pores (Lucas et al., 2019; Wang et al., 2020b) or clogging pores (see Fig. 6) (Bodner et al., 2014; Leung et al., 2015a; Koebernick et al., 2017; Bacq-Labreuil et al., 2018; Lu et al., 2020; Sullivan et al., 2022). Several scholars held that the root-induced change is predominantly due to the occupancy of plant roots in soil pores; and based on this understanding, models for capturing the root-induced change in SWRC were proposed by considering the reduced void ratio or pore throat diameter (Ng et al., 2016; Ni et al., 2019b). For example, Ng et al. (2016) introduced the root volume ratio, $R_V$, into the model proposed by Gallipoli et al. (2003), obtaining an equation that considers the obstruction caused by roots and can be used to model the water retention capacity of vegetated soils.

By contrast, others suggested that with root penetration or growth, pore-forming is more significant than pore-clogging (Bogner et al., 2010; Banwart et al., 2019; Sullivan et al., 2022). For example, Leung et al. (2023) observed an increase in porosity of a median dense, poorly-graded glass bead due to root penetration and thickening during the growth of a crop species (barley), with the assistance of advanced X-ray testing apparatus and AI-enabled image analysis techniques. Their findings confirmed the existence of both pore-clogging and pore-forming, with an emphasis on the significance of pore-forming outweighing that of pore-clogging. A recent study by Marcacci et al. (2022) provided more evidence for this point of view, i.e., roots created additional porosity and broadened the PSD. A recent review conducted by Lu et al. (2020) concluded that whether pore-forming or pore-clogging dominates depends on the types of soil and roots: fine roots at low density tend to clog soil pores and the pores in coarse-grained soils are usually blocked by plant roots. In addition, Lu et al. (2020) concluded several physical processes that roots alter the soil structure, such as pore-clogging, macro-aggregate cracking, pore-forming due to root shrinkage under drought conditions, and micro-aggregate amalgamation (see Fig. 6). In fact, different parts of the root system function differently, which has been recognized by many scholars (e.g., Jin et al., 2017; Hallett et al., 2022). The root hairs always bond soil particles together and thus increase the inter-aggregate pore spaces (Haling et al., 2013; Banwart et al., 2019; Lu et al., 2020). The root cap usually compresses the soil particles surrounding it (see Fig. 6). The thickening and lengthening of roots can compact surrounding soil particles or aggregates (Jin et al., 2017; Zhu et al., 2019; Sullivan et al., 2022). However, they were also found to disperse soil particles or aggregates (Hallett et al., 2022). The effect of root penetration on the soil structure also

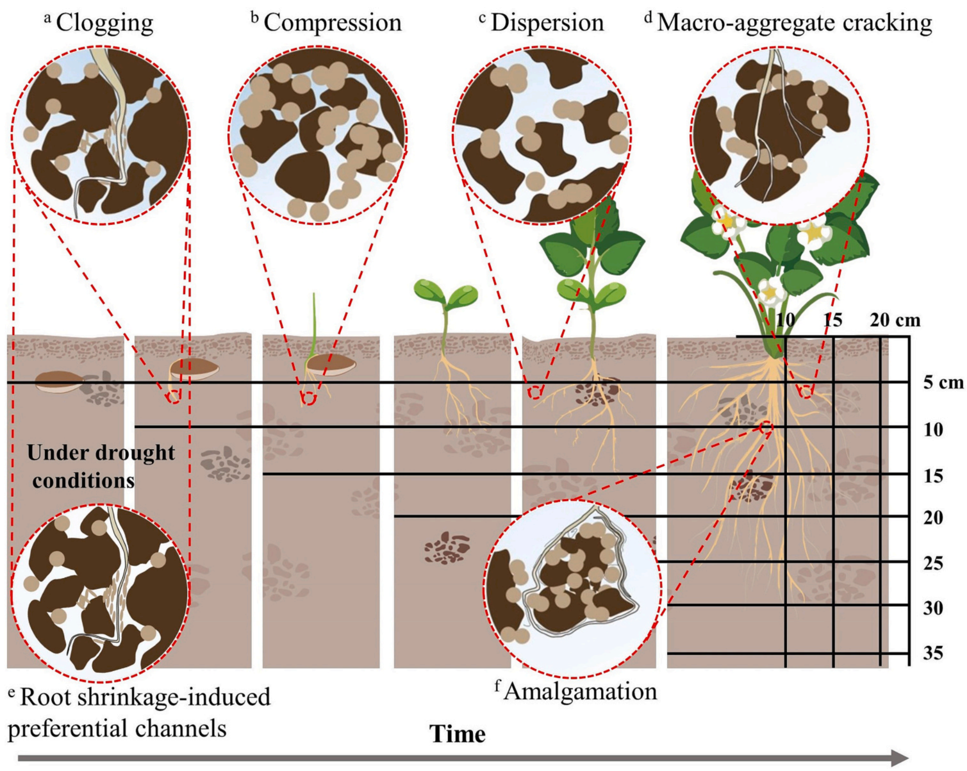


**Fig. 6.** The effect of root penetration on the soil structure: (a) pore-clogging; (b) compression; (c) microbial-induced soil aggregate dispersion; (d) macro-aggregate cracking; (e) root shrinkage-induced preferential channels; (f) micro-aggregate amalgamation.

depends on the soil water content. For example, under drought conditions, plant roots tend to penetrate deeper into the ground for acquiring water (Haling et al., 2013; Warren et al., 2014) and the shrinkage of roots (especially the grown roots) will create more macropores or cracks (Rasse and Smucker, 1998; Carminati et al., 2016; Lu et al., 2020). Besides, the type of root system has a huge impact. Fibrous roots typically clog the existing macropores or cracks (Zhu et al., 2019). Main roots always penetrate into the deep soil layers and then water channels to the deep soil layers could be formed, resulting in good pore connectivity in vertical direction. While lateral roots of some plants (e.g., tea trees) are mainly horizontal, which could improve the pore connectivity in horizontal direction (Zhu et al., 2019). Therefore, root penetration can induce or enhance the anisotropy of soil. Furthermore, the indirect effect of root penetration involves facilitating the soil aggregation by altering the local soil water dynamics (Bronick and Lal, 2005; Vereecken et al., 2022). Overall, the change in soil structure induced by root penetration is affected by the soil type, soil grain size, soil water and nutrients, root architecture, growth stage and environmental conditions, etc.

Given the significance of root penetration in modifying the soil structure (i.e., PSD, soil aggregation, pore connectivity), root penetration is of course an important factor that influences the soil hydraulic properties. A huge body of research focused on the significance of root penetration in inducing preferential flows. These studies suggested that root penetration facilitates the formation of preferential channels (e.g., Lu et al., 2020; Shi et al., 2021; Banwart et al., 2019). Devitt and Smith (2002) reported that macropores developed due to root penetration can function as preferential flow pathways, resulting in uneven water distribution in the soil. It is unfavorable for the control of some environmental, geological or geotechnical engineering problems (e.g., percolation, migration of contaminants, and shallow landslides). Because these root-induced preferential channels may accelerate the infiltration and accumulation of water to deep and potentially weak layers, thereby giving rise to landslides and slope instability or promoting migration of contaminants to groundwater (Bowmer, 1987; Alaoui et al., 2011; Wang et al., 2020b). However, under some circumstances, root penetration can enhance the water exchange, which is beneficial to the local hydrological cycle (Zhu et al., 2019; Vereecken et al., 2022). The presence of preferential flows can significantly change the soil hydraulic conductivity, especially the saturated (e.g., Trakal et al., 2013; Šípek et al., 2019). Many researchers suggested to predict the root-induced change in soil saturated hydraulic conductivity or steady infiltration rate from root characteristic parameters (e.g., root architecture, root volume percentage, root length density, root biomass density, root diameter, etc.) (Leung et al., 2015a; Leung et al., 2017; Wu et al., 2017; Jotisankasa and Sirirattanachat, 2017; Cui et al., 2019; Wang et al., 2020b; Patra et al., 2022; Zhu et al., 2022; Webb et al., 2022; Wang et al., 2023). Cui et al. (2019) studied the relationship between the volume ratio of roots within each diameter range and infiltration rate for semi-arid grassland soils. They found that the soil infiltration rate was increased with the increase of the volume ratio of roots with diameters between 0 and 2 mm, and decreased with an increase in the volume ratio of roots with diameters between 2 and 4.5 mm. Jotisankasa and Sirirattanachat (2017) also studied the relationship between root biomass density, soil saturated hydraulic conductivity and air-entry value. Their results showed that there was a root biomass density threshold for low-plasticity soils; when the threshold was exceeded, the saturated hydraulic conductivity decreased and the air-entry value increased slightly; otherwise, the saturated hydraulic conductivity increased and the air-entry value decreased with root biomass density (see Fig. 7c). However, there were experimental results inconsistent with theirs. Zhu et al. (2022) and Patra et al. (2022) observed that the soil saturated hydraulic conductivity and steady infiltration rate increased with the increasing root biomass density (see Fig. 7b). And Webb et al. (2022) found that the relationship between root biomass density and saturated hydraulic conductivity depends on the type of vegetation (see Fig. 7a). That is to say, root biomass density may not be an essential driving factor for soil permeability. Additionally, root length density is positively correlated to the soil saturated hydraulic

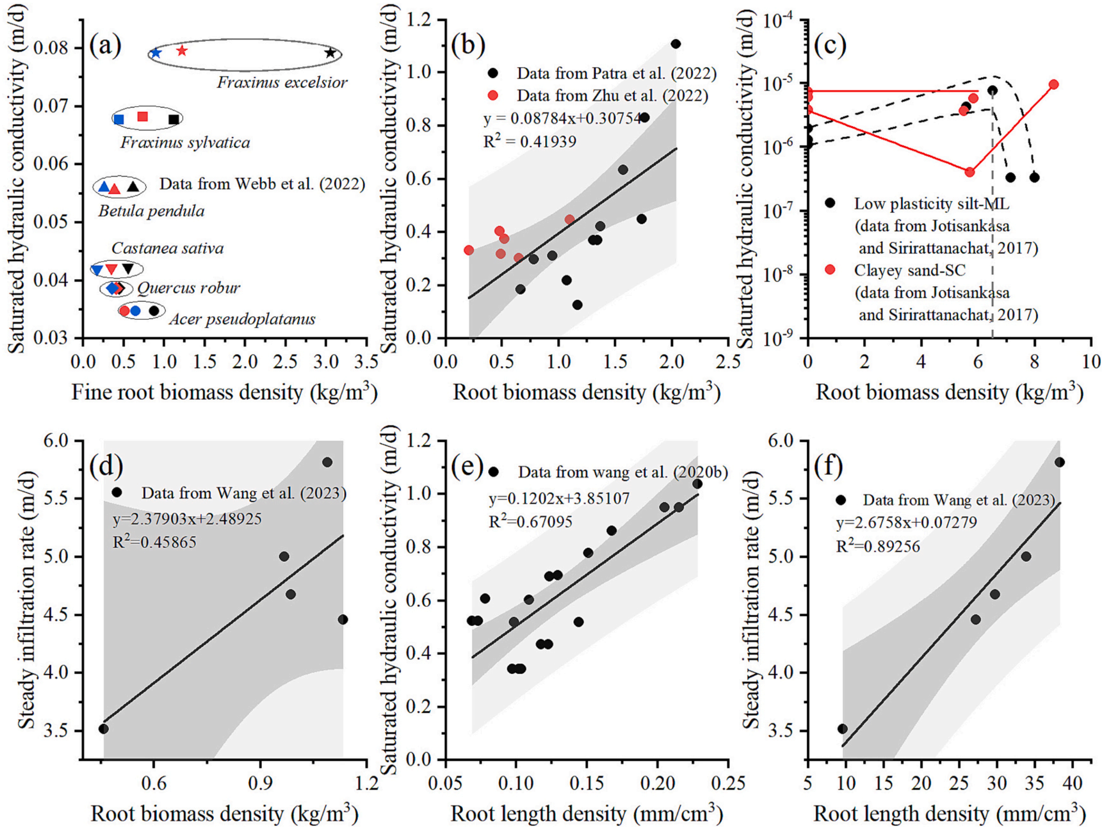

**Fig. 7.** Relationship between root biomass density, root length density and saturated hydraulic conductivity or steady infiltration rate. Note that the black, blue and red color in figure (a) represent sampling depths of 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m, respectively.

conductivity and steady infiltration rate, with high correlation coefficients (i.e., 0.67, 0.89; see Fig. 7e, f). Compared to root biomass density, the variations of saturated hydraulic conductivity and steady infiltration rate with root length density are much more evident (Lu et al., 2020; Webb et al., 2022; Wang et al., 2020b; Wang et al., 2023). However, a study carried out by Leung et al. (2015a) showed that plants could reduce the saturated hydraulic conductivity of soil, while the saturated conductivity of vegetated soil had no significant relationship with the root length. Ng et al. (2020) suggested that the saturated hydraulic conductivity of vegetated soil did not always increase with an increase in root length density. Their results demonstrated that the saturated permeability coefficient remains initially unchanged and subsequently decreases with root length density. However, it then increases as root density exceeds 2 $cm/cm^2$. Owing to the complexity of the root penetration process, systematic studies on the influence of root penetration on the soil water retention capacity are very scarce up to now.

The root architecture definitely influences the effect of root penetration on the soil hydraulic properties. However, a precise relationship between the root architecture and soil hydraulic properties could not be obtained since most of the current studies were conducted on single plant species and based on soil column tests indoors or outdoors, in which the container (stainless, woody, PVC, acrylic, etc.) with specific height and diameter for soil column can limit the growth of root system. For these reasons, the relationship between the root architecture and soil hydraulic properties is essentially linked to the interaction between plant species and soil hydraulic properties. For example, the suggestion was made that horizontal root system may impede water infiltration, while inclined and vertical root system may facilitate deep soil water flow (Ghestem et al., 2011; Wang et al., 2020b). Wang et al. (2020b) measured the saturated hydraulic conductivities ($K_s$) of root-soil composites with six root architectures (i.e., V-, M-, W-, VH-, H-, R-type, representing six plant species), and observed that H-type exhibits the smallest $K_s$, followed by VH-, M-, R-, V-, and W-type, and $K_s$ is generally positively correlated to root length density, root volume density and root fractal dimension (a high fractal dimension demonstrates a large proportion of fine roots). Some researchers also measured the saturated (or near-saturated) hydraulic conductivity and water retention capacity of soils under various land use types, such as grassland, shrubland, woodland, and cropland; and found considerable differences among them (Fu et al., 2003; Chen et al., 2007; Zhao et al., 2014; Zhu et al., 2022). However, the relationship between the root architecture and soil hydraulic properties remains unclear due to the difficulty in parameterizing the root architecture and potential confounding effects from other environmental factors and management practices that may obscure the distinct influence exerted by plant roots. Moreover, root parameters such as the root volume, length, and biomass, as well as the above-ground plant traits, have consistently been measured in most studies with limited attention given to the configuration of roots (Boldrin et al., 2017; Ng et al., 2020; Chen et al., 2021; Webb et al., 2022; Zhu et al., 2022; Boldrin et al., 2022).

## 5. Effects of root water uptake on the soil structure and soil hydraulic properties

Root water uptake, a critical part of the hydrological cycle, is mainly a passive process driven by the difference in water potential in the soil-plant-atmosphere continuum, which compensates for the transpiration (Carminati et al., 2009; Carminati, 2012; Katul et al., 2012; Deng et al., 2017). Root water uptake plays a key role in shaping the water profile in the soil and the distribution of water potential in the vadose zone. Fig. 8 provides a schematic diagram of the hydraulic pathway in vascular plants, these plants transport water from the rhizosphere soil to leaves through the xylem and phloem. It is worth mentioning that water

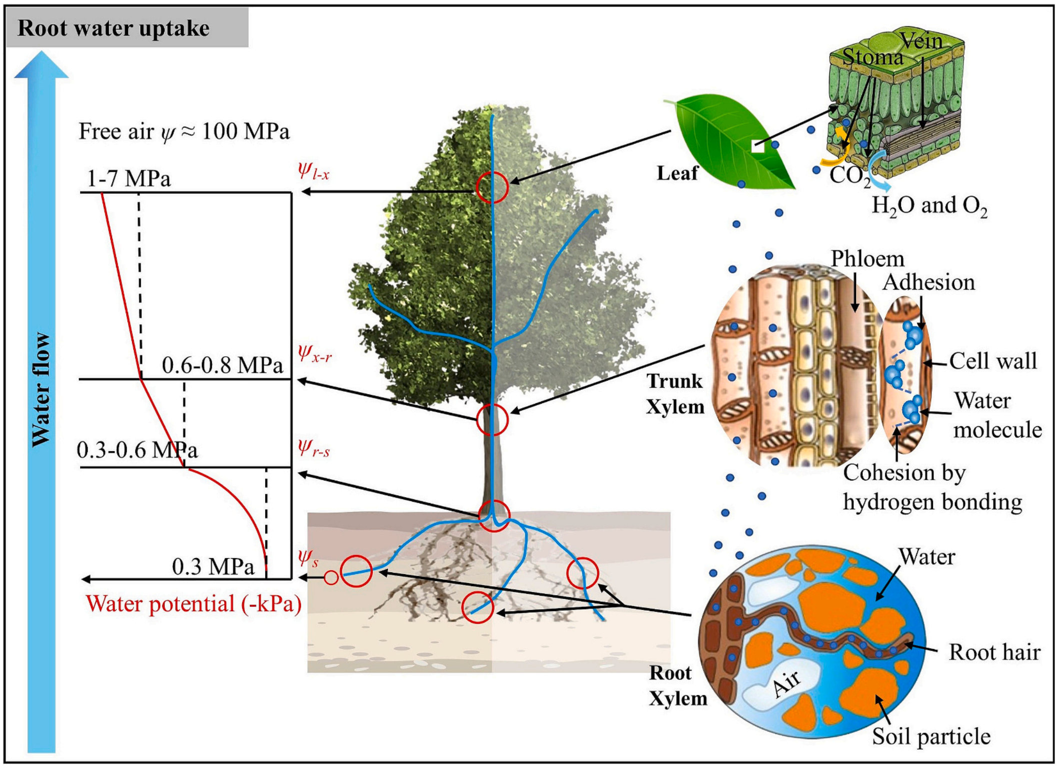


**Fig. 8.** Overview of water transport in the soil-plant-atmosphere continuum. Typical distribution of the water potential in the soil-plant-atmosphere continuum is shown. The xylem carries a flow of water under the water potential difference between leaves and roots.

molecules transport in the xylem following the cohesion-tension theory and their movement in the phloem is governed by the Münch hypothesis (Tyree, 2003; Ryan and Asao, 2014; Fatichi et al., 2016; Novick et al., 2016). Root water uptake is mainly controlled by the opening and closing of stomata, which are water potential regulators of plants, and can regulate the water potential difference between roots and leaves and affect the transpiration rate according to the environmental condition (e.g., solar radiation, atmospheric humidity, $CO_2$ concentration, etc.) (Leung et al., 2015b; Fatichi et al., 2016; Carminati et al., 2016; Carminati and Javaux, 2020; Cai et al., 2022a; Ng et al., 2022). The closing and opening of stomata help maintain the balance between transpiration demand and water supply of the soil-plant-atmosphere continuum (Gonzalez-Ollauri and Mickovski, 2017; Cai et al., 2022a). When the water potential difference between leaves and roots is greater than the gravitational potential, water transports from roots to leaves, which promotes roots absorb water from the rhizosphere soil (Fatichi et al., 2016). Meanwhile, with water transports, the temperature of leaves decreases, which in turn reduces the respiration rate and promotes the growth of plants (Katul et al., 2012). Root water uptake is plant-specific. A series of investigations conducted by Boldrin et al. (2017, 2021, 2022) revealed significant variation in the transpiration (or water uptake) efficiency among different species, i.e., deciduous species exhibited twice the transpiration efficiency and leaf conductance to water vapor of evergreen species. In fact, even within the same species, the transpiration (or water uptake) efficiency may be varied, since both root system (including its symbiotic mycorrhiza) and above-ground development influence the water uptake capacity of plants (Linderson et al., 2007; Zarebanadkouki et al., 2013; Sidle and Bogaard, 2016; Boldrin et al., 2017; Boldrin et al., 2018; Sonkar et al., 2019; Ng et al., 2020; Boldrin et al., 2021; Cai et al., 2022b). The influencing factors can be divided into two groups, i.e., transpiration demand and water supply (Vereecken et al., 2022; Cai et al., 2022a). As water in the rhizosphere soil is extracted by roots, the soil structure and soil hydraulic properties in the rhizosphere will change.

For the soil structure, on one hand, root water uptake can affect the soil structure dramatically, which is proved by many scholars (e.g., Materechera et al., 1992; Colombi et al., 2017; Colombi et al., 2021). Their research revealed that root water uptake can cause drying of the rhizosphere soil, resulting in the compaction of surrounding soil and finally producing macropores (i.e., micro-cracks). For instance, Colombi et al. (2021) used an artificial root to simulate the process of root water uptake and studied the relationship between the soil structure and intensity of root water uptake. They found the higher the intensity of root water uptake was, the more the macropores developed in soil. On the other hand, the rhizosphere soil may experience more drying-wetting cycles due to root water uptake (Jotisankasa and Sirirattanachat, 2017; Bordoloi et al., 2020a, 2020b; Shi et al., 2021). And drying-wetting cycles have a significant influence on the soil structure because the particle shape, particle arrangement, particle aggregation, chemical cementation might be modified due to the stress state changes during drying and wetting (Burton et al., 2015; Ma et al., 2020; Tang et al., 2021; Wen et al., 2022; Ng and Peprah-Manu, 2023). For example, Wen et al. (2022) studied the microstructure of a granite residual soil subjected to drying-wetting cycles using the X-ray computed tomography technique; they found that the pore connectivity and pore throat diameter reduced with the increasing number of drying-wetting cycles. Although some emerging techniques (e.g., X-ray computed tomography, nuclear magnetic resonance technique, and neutron tomography) can be used to capture the changes in soil structure induced by drying or wetting, few of these techniques have been used to investigate the effect of root water uptake on the soil structure. This may be because the impact of root water uptake on the soil structure requires a lot of time (days or even months), and it is very expensive and almost impossible to scan a soil sample for a long time using these advanced techniques. In addition, in the nearly closed chamber of the scanner, the physiological activity of plant is different from that in nature.

The effect of root water uptake on the soil hydraulic properties has been investigated by some scholars (e.g., Ng and Leung, 2012; Leung et al., 2015b; Ni et al., 2017; Zhu et al., 2018; Ni et al., 2019a; Wu et al., 2022; Ng et al., 2022). Their research showed that the soil water profile changes due to root water uptake, and soil suction increases. For instance, the results of Ng and Leung (2012) and Leung et al. (2015b) indicated that root water uptake has a significant influence on the hydraulic conductivity of unsaturated soil since soil suction varies. Zarebanadkouki et al. (2013) observed the water redistribution due to lupine root water uptake using the neutron radiography technique, and their results showed that the water infiltration in the soil was remarkably influenced due to water uptake by lateral roots. Many studies reported the changes in soil suction or soil water retention behavior induced by plant roots and transpiration (i.e., root water uptake) (e.g., Rahardjo et al., 2014; Scholl et al., 2014; Leung et al., 2015a, 2015b; Ng et al., 2015, 2016; Song et al., 2017; Zhu et al., 2018; Ni et al., 2019b; Bordoloi et al., 2020b). For example, Ni et al. (2017) investigated the variation of plant transpiration- or root water uptake-induced suction during sunlight and rainfall, and they found that soil suctions below the vegetated grounds at 1 m depth were always higher than that at the same depth below the bare grounds. Boldrin and his colleagues' studies (on 10 woody species belonging to deciduous and evergreen species, and 6 herbaceous species belonging to forbs, greases and legumes) revealed that daily evapotranspiration resulted in up to five times greater water loss compared to fallow soil, and the specific leaf area, root length density and root: shoot ratio showed significant and positive correlations with the transpiration-induced suction (Boldrin et al., 2017; Boldrin et al., 2021; Boldrin et al., 2022). Their investigations placed more emphasis on the variations among different plant species. A study by Ng et al. (2015) can be considered groundbreaking in quantifying the impact of root architecture on root water uptake and transpiration-induced suction. The study presented new analytical solutions for the pore water pressure distribution under both steady and transient conditions, taking into account the influence of water uptake by different root architectures (uniform, triangular, exponential, and parabolic). The subsequent numerical modelling conducted by Ng and his group suggested that the suction produced by an exponential root architecture was the largest, followed by triangular, uniform and parabolic root architectures (Liu et al., 2016; Liu et al., 2018; Zhu et al., 2018; Feng et al., 2020; Ng et al., 2021). Furthermore, the centrifuge modelling conducted by them using artificial roots (cellulose acetate, CA) validated the findings of their numerical models, that is, the heart-shaped root (representing exponential root) provided additional hydraulic contact with surrounding soil for more water uptake to take place that the other two roots (tap- and plate-shaped) (Ng et al., 2015; Ng et al., 2021).

Some scholars argued that the effect of root water uptake (or plant transpiration) on the soil hydraulic properties can be practically negligible in certain situations (e.g., high humidity, nighttime, or winter) (Snyder et al., 2003; Leung et al., 2015a, 2015b; Ng et al., 2016). However, Leung et al. (2015b) studied the effect of vegetation on soil suction under dark and sunlight conditions after being subjected to a rainfall event (a return period of 100 years), and found that under dark condition the suction in vegetated soil at the depth of 8 cm was higher than that in bare soil (see Fig. 9a, c), and the suction in vegetated soil in the light is higher than that in the dark (see Fig. 9b, d). Note that the bare soil and vegetated soils had the same dry density and initial water content. That is to say, root water uptake indeed leads to soil suction increase and vegetated soil needs more water than bare soil to reach the same soil suction (vegetation apparently increases the soil water retention capacity by root water uptake). For this reason, root water uptake can affect the unsaturated hydraulic conductivity of soil because it is intimately related to soil suction. However, in general, there is still a

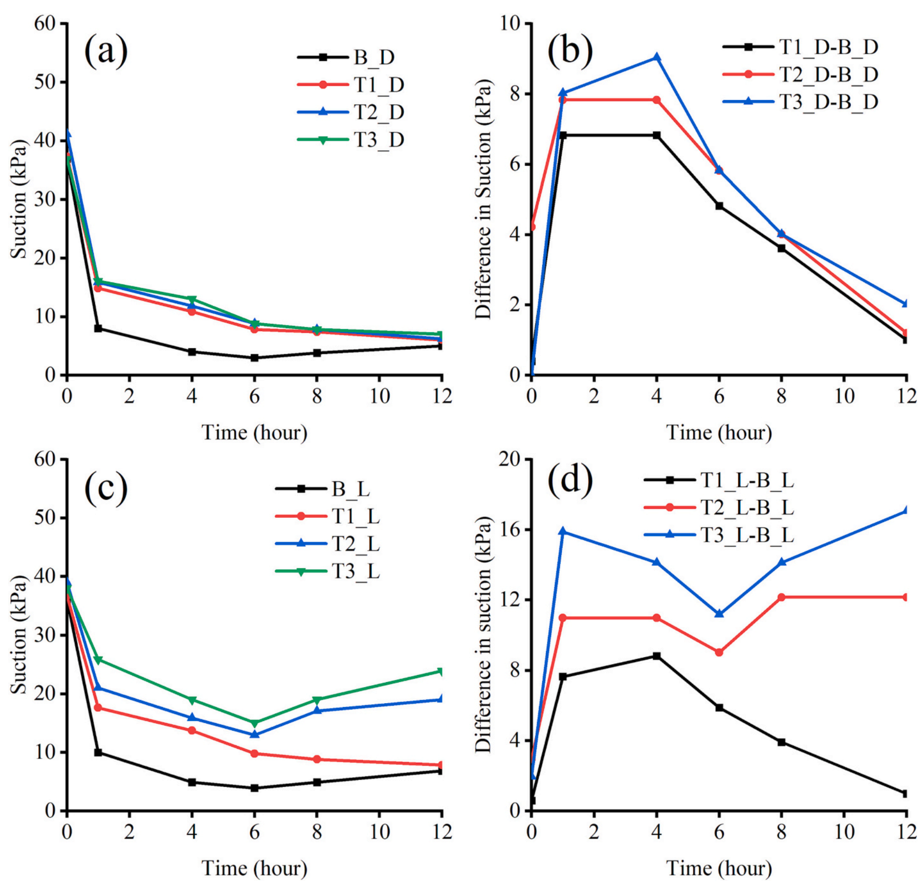


**Fig. 9.** (a, c) The temporal variation of suction for bare soil and vegetated soils (data from Leung et al. (2015b)); (b, d) difference in suction (the suction of vegetated soil subtracts that of bare soil at the same time) varies with time under dark/sunlight condition.

lack of research on the influence of plant transpiration or root water uptake on the soil hydraulic properties so far, although transpiration is a major way of soil water loss. In addition, although the extra suction in the soil induced by plant transpiration or root water uptake has been observed or measured by a number of researchers, the specific effect of transpiration or root water uptake on the soil hydraulic properties (hydraulic conductivity and soil water retention behavior) remains unclear or unknown. We think there are three main reasons. First, the soil structure has a control over the soil hydraulic properties, and the soil hydraulic properties evolve as the soil structure varies due to root water uptake. The effect of root water uptake on the soil structure may require a long time to be evident (for example, the change in soil structure due to an increase in the number of drying - wetting cycles), as mentioned above; so, root water uptake may also take a long time to have an evident effect on the soil saturated hydraulic conductivity and SWRC. Then, plants are living organisms, root water uptake is always accompanied by root growth; so, the effects of root water uptake and root penetration are intertwined, it is difficult to identify the extent to which each of them affects the soil structure and soil hydraulic properties. Last but not least, plant transpiration or root water uptake is affected by many factors, including the type and properties of soil, plant species, growth stage, environmental factors and so on; so, the effect of root water uptake must be time-dependent. For these reasons, quantifying the effect of root water uptake on the soil hydraulic properties remains difficult, few attempts have been made to precisely measure the changes in soil water retention capacity and hydraulic conductivity induced by root water uptake.

## 6. Effects of root decay on the soil structure and soil hydraulic properties

Root decay plays a critical role in the functioning of soil ecosystem as well as in modifying the soil structure and soil hydraulic properties in the Earth's critical zone (Wu et al., 2021; Naeem et al., 2022; Sullivan et al., 2022). It occurs throughout the whole lifespan of plants and the decomposition of roots depends on many factors, such as plant species, root architecture, root physiology, root chemical composition and intense plant-plant competition and soil environment (Zanne et al., 2015; Ng et al., 2020; Naeem et al., 2022). A number of researchers have observed that more bio-macropores and bio-micropores are formed in soil due to root decay, which leads to changes in the soil PSD (Lei, 1988; Ghestem et al., 2011; Guo et al., 2019; Ni et al., 2019b; Zhang et al., 2021a; Wu et al., 2021; Cui et al., 2022). For instance, Lei (1988) showed that root decay can form lots of tube channels in loess soils. Guo et al. (2019) also found that root decay can increase the number of preferential flow channels. There are three main reasons for this phenomenon. First, it is noteworthy that the dry biomass of roots would greatly reduce as they decay (Smith et al., 2014; Ni et al., 2019b). Next, root decay could result in an alkaline environment in the rhizosphere, which facilitates the precipitation of carbonates. This process can lead to the inner walls of pores being well coated with carbonate cementations, allowing these previously root-occupied pores to remain intact after losing root support (Gao, 1981). Last, root decay can increase the soil organic matter content and promote the soil aggregation process by providing organic binding agents (Wu et al., 2021; Shi et al., 2021; Sullivan et al., 2022). Generally, the organic matter produced by root decay can interact with soil minerals and form large aggregates (Abiven et al., 2009; Reichenbach et al., 2021; Sullivan et al., 2022). The soil aggregation process could render a soil high macro-porosity and good pore connectivity (Ni et al., 2019b; Wu et al., 2021; Sullivan et al., 2022; Cui et al., 2022). Moreover, the decayed root also increases the microbial activity and affects the soil structure further (Banwart et al., 2019; Sullivan et al., 2022). In summary, root decay plays an active role in increasing the soil macro-porosity, improving the pore connectivity, modifying the grain-size distribution and contact angle of soil, thereby leading to alterations in the soil structure and soil hydraulic properties.

Most previous studies presented that root decay can increase the soil hydraulic conductivity (Shao et al., 2017; Ni et al., 2019b; Ng et al., 2020; Wu et al., 2021; Boldrin et al., 2022; Cui et al., 2022). Ni et al. (2019b) conducted an experimental study to investigate the impact of root decay on the saturated hydraulic conductivity and water retention capacity of vegetated completely decomposed granite (CDG). Their results revealed that root decay can reduce the water retention capacity and increase the saturated hydraulic conductivity of vegetated CDG. In their study, a parameter, $\eta$ (root decay ratio, fraction of the return of soil pore space (in volume) due to root shrinkage upon decay), was introduced to quantify the extent of root decay, and a new SWRC model considering root decay was established based on the model of Ng et al. (2016). The root traits (root volume ratio and root decay ratio) incorporated in their SWRC model are highly time-dependent. However, the lack of data on temporal changes in these vegetation root traits hinders the model's ability to predict alterations in the water retention capacity of vegetated soil over time. Their experimental results are presented in Fig. 10a, b, it can be observed that the air-entry value of vegetated soils decreases with the time of growth. Note that bare soil has a $\eta = 0$ and $\eta$ increases with the time of growth. That is to say, $\eta$ influences the air-entry value; and there exists a decay ratio threshold. To be exact, the air-entry value of vegetated soil is greater than that of bare soil when $\eta$ is less than this threshold, and vice versa. The relative variation of saturated hydraulic conductivity (compared to that of bare soil) decreases first and then increases with $\eta$ (see Fig. 10b). This is similar to the finding of Jotisankasa and Sirirattanachat (2017), who found that there was a root content (root biomass per unit volume) threshold for the saturated permeability of vegetated silt; the soil saturated permeability reduced within this threshold, and increased beyond it. Meanwhile, Ni et al. (2019b) and Smith et al. (2014) observed that the biomass of decayed roots was reduced by >80 % compared to that of alive roots. This indicates that the effect of root decay on the soil hydraulic properties might be related to the root biomass content. Cui et al. (2022) compared the effects of alive roots and decayed roots on the initial and steady infiltration rate, their results showed that given the same plant species, decayed roots can remarkably increase the soil infiltration rate compared to alive roots. Fig. 10c, d presents the relative variations of initial infiltration rate and steady infiltration rate. It can be observed that the relative variations of initial infiltration rate and steady infiltration rate of the soils with decayed Korshinsk peashrub (*C. korshinskii*) are more than one time greater than those of the soils with alive Korshinsk peashrub (*C. korshinskii*). Wu et al. (2021) carried out a field test to examine the temporal effect of decayed roots on the water infiltration in planted forestland. Their results, presented in Fig. 10e, f, showed that the relative variations of steady infiltration rate and initial infiltration rate increase with the decaying time (from 7.7 % to 238.5 %, from 61.3 % to 151.3 %, respectively). These results suggest that root decay facilitates planted land maintaining a relatively high steady infiltration rate compared to bare land. However, the study carried out by Lei et al. (2022) showed that root decay could reduce the soil hydraulic conductivity under certain conditions because the soil organic matter content increase could make soil hydrophobic. While they found that as time went by, the water repellency of soil decreased, and the hydraulic conductivity of soil increased, which was consistent with the results of Ni et al. (2019b). A recent meta-analysis also demonstrated that root decay can increase the soil organic matter content and there is a negative relationship between the soil organic matter content and steady infiltration rate (Shi et al., 2021). Ni et al. (2019b) also introduced the decay ratio, $\eta$, into the Kozeny-Carman equation (Carman, 1937) for predicting the saturated hydraulic conductivity of vegetated soils. The model performed commendably in predicting the saturated permeability coefficient of vegetated soils, as demonstrated in the study by Ni et al. (2019b). However, the original Kozeny-Carman model has been found inadequate in accurately predicting the saturated hydraulic conductivity of fine-grained soils (Ren et al., 2016; Ren and Santamarina, 2018); therefore, it is necessary to validate this model using more experimental

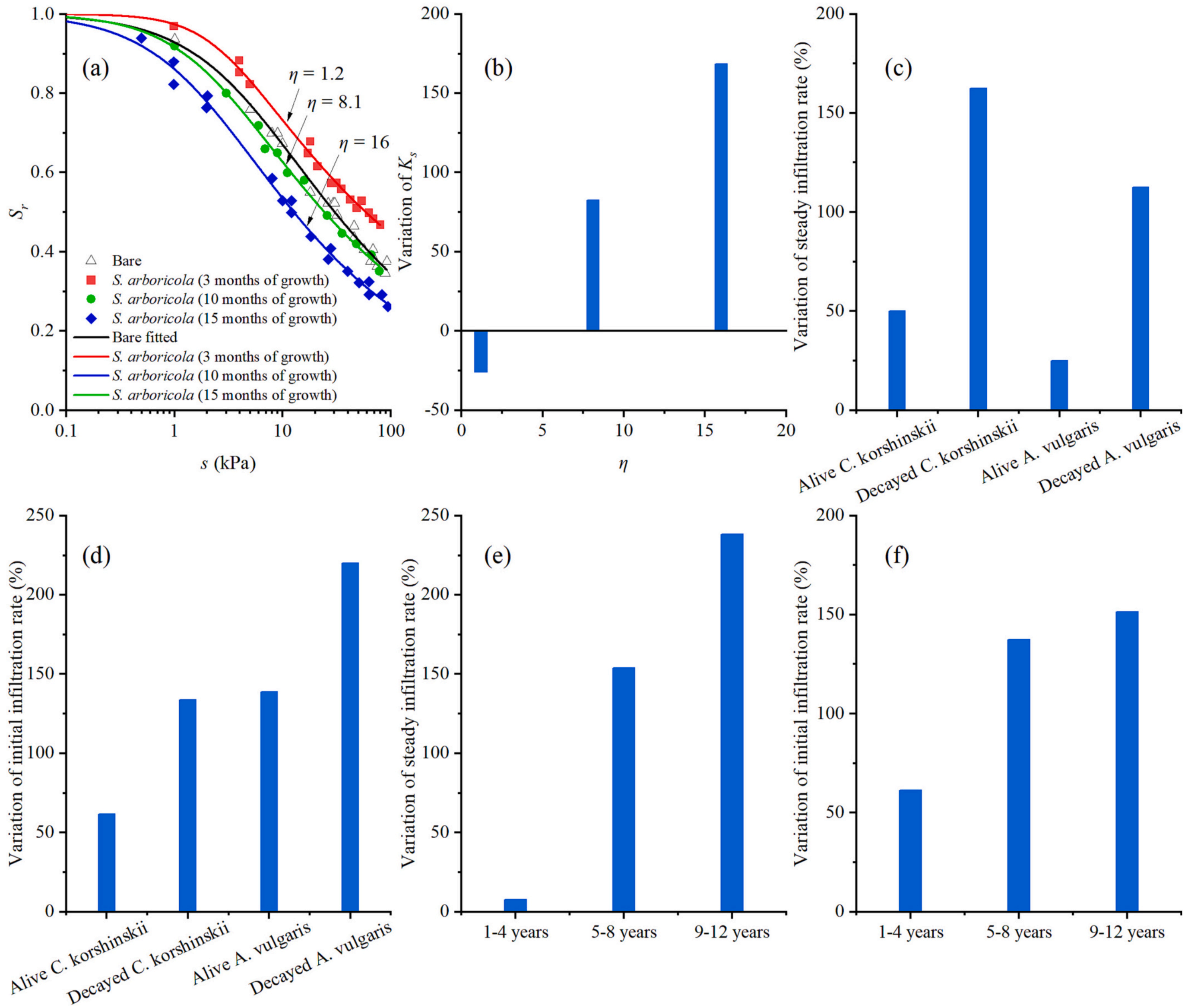


**Fig. 10.** (a) SWRCs of vegetated soils with different decay ratios, $\eta$ (data from Ni et al. (2019b)); (b) the relative variation of saturated hydraulic conductivity (= ($k_s$-$k_{s\_bare}$)/$k_{s\_bare}$*100 %) (data from Ni et al. (2019b)); (c) and (d) the variations of steady infiltration rate and initial infiltration rate, respectively (data from Cui et al. (2022)); (e) and (f) the variations of steady infiltration rate and initial infiltration rate, respectively (data from Wu et al. (2021)).

data from vegetated fine-grained soils. Moreover, potential changes induced by any root effects in the specific area of vegetated soil and viscosity of pore fluid were not considered, despite recent studies highlighting that vegetation can significantly increase both the soil specific area and pore fluid viscosity (Naveed et al., 2019; Arthur et al., 2023). The specific area of a soil is closely related to its GSD, which can be easily modified by root exudation or root penetration (Chapuis, 2012; Lehmann et al., 2021).

Yet, existing studies have provided a fundamental understanding of the effect of root decay on the soil hydraulic properties: root decay and the associated increase in microbial biomass result in a rise in the soil organic matter content, which could make the soil hydrophobic and reduce the permeability of vegetated soil compared to bare soil; while as organic materials are gradually decomposed, the soil hydrophobicity is decreased and the soil permeability is increased. However, the relationship between the extent of root decay and soil hydraulic properties remains unclear. Although Ni et al. (2019b) introduced a parameter indicating the extent of root decay (decay ratio), how the decay ratio of a specific plant varies with the time of growth (or the decaying time) has not been precisely observed. It is believed that the decay rate is influenced by many factors, including the soil properties and characteristics of roots (or plant species). In most previous studies, it has been speculated that the initial decrease in saturated hydraulic conductivity or infiltration rate may be attributed to the alteration of soil hydrophobicity. And it is believed that the soil hydrophobicity diminishes over time, ultimately leading to an increase in the saturated hydraulic conductivity or infiltration rate. However, the soil hydrophobicity as well as its variation over time after root decayed have rarely been quantitatively characterized. Furthermore, the indirect effect of root decay (rise in microbial biomass) was not considered in most studies (to what extent does the increased microbial biomass due to root decay influence the soil hydrophobicity?). Last but not least, the detailed chemical components of decayed roots of a specific plant under natural conditions are not clear (are all the organic materials produced by root decay hydrophobic?). Therefore, the impact of root decay on the soil structure and hydraulic properties requires further exploration.

## 7. Summary and future perspectives

Effects of plant roots on the soil structure and soil hydraulic properties have been studied in the past few decades. Published studies have provided a fundamental understanding of the effects of plant roots, which are divided into four in this review, namely, root exudation, root penetration, root water uptake and root decay. Root exudates modify the soil structure and soil hydraulic properties by absorbing large volumes of water, altering the aggregate size and stability, the contact angle of soil, and the viscosity and surface tension of pore fluid. Root penetration changes the soil structure and soil hydraulic properties by producing pores or clogging pores. Root water uptake can increase the soil suction and may induce the formation of micro-fissures and macropores around roots. Root decay modifies the pore structure and water repellency of soil, then producing changes in the soil structure and soil hydraulic properties. Many results have been achieved, but there still remains a significant challenge in comprehending and quantifying the effects of plant roots on the soil structure and soil hydraulic properties. Some questions and disputes that require further investigation in the future are as follows.

(1) Current research on the effect of root exudation on the soil structure and soil hydraulic properties still has some deficiencies. 1) It is not clear which specific components of root mucilage cause changes in the soil structure and hydraulic properties. The primary challenge lies in the collection of root exudates at various stages of plant development or under diverse abiotic stress conditions. Therefore, innovative testing methods or advanced extraction techniques are required to collect root exudates, the composition of which can be determined using gas chromatography–mass spectrometry (GC–MS) or liquid chromatography-mass spectrometry (LC-MS). 2) There were many studies on the influence of root exudates of crops on the soil water retention capacity, while very little attention has been paid to the influence of root exudates of other plant species. For soil or slope improvement purposes, the composition and effect of root exudates of shrubs or herbaceous plants, commonly seen in engineered slopes, may be of greater interest to engineers. 3) There is a lack of models that consider the effect of root mucilage or its concentration on the soil hydraulic properties.

(2) For the effect of root penetration on the soil structure and soil hydraulic properties, 1) the temporal variation of the effect of root penetration or growth on the soil structure and soil hydraulic properties has rarely been investigated; the conditions (including soil, root parameters and time) necessary for pore-forming or pore-clogging remain unclear; 2) the effect of root penetration on the soil hydraulic properties has rarely been characterized and related to root parameters (e.g., root area index, root biomass density; root length density); 3) studies on the variations of root parameters over time are lacking, making it difficult to predict transient changes in the soil structure and soil hydraulic properties due to root penetration or growth. Planting vegetation in transparent soil or containers with a very small size (for instance, 1 cm diameter) and utilizing X-ray μCT imaging could facilitate the visualization of grain or pore kinematics and the exploration of micro-scale soil-root-water physical interaction. Note that the phase segmentation of CT images of multi-phase unsaturated vegetated soil may pose a challenge due to the similar X-ray attenuation coefficients of water and moist roots. A notable example is the study conducted by Leung et al. (2023), which effectively address this challenge through the application of machine learning technique. However, as mentioned before, this method only allows for the visualization of roots during the early stages of plant development or root segments due to the small sample size.

(3) For the effect of root water uptake on the soil structure and soil hydraulic properties, 1) the effect of root water uptake may need a long time to be evident, such that it is difficult to observe changes in the soil structure due to root water uptake or distinguish the effect of root water uptake from the effect of root growth. Artificial roots with diverse root architecture, specific root length and root biomass fabricated by 3D printing technology have already been employed for research purposes. Meanwhile, ceramic disk and air supply devices were used to simulate the process of root water uptake. Thus, it was possible to differentiate between the hydrological reinforcement provided by vegetation roots (resulting from root water uptake) and the mechanical reinforcement of roots. 2) The specific effect of root water uptake on the soil hydraulic properties remains unclear or unknown, as plant transpiration is a time-dependent process influenced by numerous factors; 3) modelling the effect of root water uptake on the soil hydraulic properties remains difficult and rare.

(4) For the effect of root decay on the soil structure and soil hydraulic properties, 1) the temporal effect of root decay on the soil structure and soil hydraulic properties has rarely been studied. Smart real-time monitoring technology and machine learning could be used to solve this problem, which regards the studied plants as 'living sensors'. Based on some easily measurable plant traits such as the canopy temperature and leaf color, a real-time model could be developed to indirectly measure the plant decay parameters and soil hydraulics. Meanwhile, the hydraulics of vegetation could be used to deduce the changes in pore structure of vegetated soils. 2) The exact components of decayed roots and how the decay ratio varies over time are not very clear; the decaying substances of local roots at different time points should be extracted and analyzed for a specific plant. The growing volume of data and the application of machine learning could enable the acquisition of global plant data by integrating local datasets. 3) The indirect effect of root decay (rise in microbial biomass) was not considered in most studies.

## CRediT authorship contribution statement

**Tao Xiao**: Conceptualization, investigation, figure preparation, and manuscript writing. **Ping Li**: Conceptualization, manuscript writing & revision, supervision. **Wenbin Fei**: Investigation, review & editing. **Jiading Wang**: Supervision.

## Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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