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Root zone in the Earth system

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Abstract: The concept of "root zone" is widely used in hydrology, agronomy, and land surface process studies. However, the root zone still lacks a precise definition. More essentially, the importance of root zone in the Earth system science is largely under explored. In addition, the methodology to estimate root zone is still controversial. In this study, we firstly attempted to clarify the definition of the root zone by comparing with various "similar" terms, such as rooting depth, soil depth, vadose zone, rhizosphere, and critical zone, to bridge the gaps within and between traditional disciplinary boundaries. Secondly, we found that, from a hydrological and thus water-centric perspective, the root zone holds profound implications across all the spheres of the Earth system, including biosphere (living organisms), hydrosphere (water), pedosphere (soil), lithosphere (rock), and atmosphere (air), through various exchange fluxes of mass and energy. The role of the root zone in the Anthropocene is elaborated as well, including the intensifying impacts of climate change and agriculture, along with implications for nature-based solutions and planetary stewardship. Thirdly, for root zone estimation, we underscore that the theoretical foundation of the traditional reductionist approach to understand and model the root zone is

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problematic due to the complex and dynamic nature of root zone functions. We advocate for a shift towards a holistic ecosystem-centered perspective, which offers a more realistic, simplified, and dynamic representation of the root zone in Earth system science.

1 Introduction

During the Devonian Period, 416 to 360 million years ago, roots were an early development in the plant's evolution history, even before leaves (Kenrick and Strullu-Derrien, 2014). The development of root systems was a critical biological innovation that subsequently enabled land plants to spread and colonize continental interiors, where previously, their limited simple rhizoid-based rooting systems confined them to areas immediately adjacent to bodies of water (Smart et al., 2023). The rapidly extending functionality and complexity of the root system performs essential functions necessary for the survival and development of plants, such as anchoring them to a substrate, absorbing water and nutrients, and storing photoassimilates (Shekhar et al., 2019). The rapid expansion of terrestrial plants, enabled by the newly developed rooting system, caused a dramatic increase in physical and chemical rock weathering and terrestrial photosynthesis capability, which massively drew down the atmospheric CO_2. This likely triggered the ice age and the mass extinction in the late Devonian (Smart et al., 2023). The rooting system, at its first appearance, completely transformed the entire biosphere and their abiotic environment on the planet.

Roots act as pioneers of biological activity, representing a definitive line between sterile sediments and living soils. Fossil evidence showed that deeper soils and larger plants appeared almost simultaneously (Kenrick and Strullu-Derrien, 2014). There is positive feedback between soils and plants, mediated by the roots. Larger plants generally require more stable and comparatively deeper soils, and plant roots contribute to soil formation. Thus, in some places, the deep roots for groundwater access may have acted as a direct agent to accelerate weathering and soil formation through physically widening rock fractures, inviting water and hastening other physical and chemical weathering, and increasing the acidity of soil and groundwater that further enhanced chemical weathering (Maeght et al., 2013). Thus, the evolution of plant root systems had not only influenced the local-scale soil microenvironment and individual plant life cycles, but also the weathering of the lithosphere and the formation of the pedosphere. Hence, root system development has had far reaching impacts on the evolution of the atmosphere, the hydrosphere and the entire Earth system (Hetherington, 2019).

The root zone, where plants developed a place to adapt to the environment through long-term evolution, forms the substrate of the terrestrial ecosystem and hence is a crucial element of the critical life zone on Earth (Banwart et al., 2017). It is well demonstrated that the soil forms an ecosystem full of micro-biotic and macrobiotic life (Ponge, 2015). Fungi forming dense underground networks live in symbiosis with vegetation, exchanging nutrients for carbon, which makes them responsible for the larger part of subterranean carbon storage (Domeignoz-Horta et al., 2021). Through evolution and natural selection, the ecosystem has found ways to make best use of the climatic and geological resources.

Plants together with micro-organisms alter soil hydraulic properties and water-cycle processes through creating soil macropores and adding soil organic matter. Macropores created through living or decayed roots are large cracks or pores that facilitate infiltration and fast water drainage, thus reducing the time to soil saturation that may cause root rotting. The cementation by organic matter from dead roots affects the internal structure of soils. Thus, soils with high organic matter commonly have high porosity and high field water holding capacity to constrain water in soil pores. Thus, the root zone is the result of long-term co-evolution of the biosphere, hydrosphere, and pedosphere, depending on the climatic and geological boundary conditions.

In the past decades, the root zone has attracted growing attention from different disciplines, including hydrology, agronomy, plant biology, soil physics, atmospheric science, and landscape engineering, for different reasons. However, there is still a lack of review on the basic concept of the root zone, particularly in the context of Earth system science. Thus, there is an urgent need to clarify the definition of the root zone and to bridge the knowledge gaps between traditional disciplinary boundaries.

2 What is the root zone?

The first challenge lies in the difficulty of defining a common, unambiguous language to accurately communicate between the variety of disciplines involved in root zone research and subsequently between the broader disciplinary fields of hydrology, ecology, climatology, pedology, agronomy, horticulture, forestry, etc.

In its most general form, the root zone is the upper part of the unsaturated zone that supports vegetation rooting, where water and nutrients are potentially available to support plants (Sprenger et al., 2019). The storage of moisture in the root zone is difficult to determine because of the complex relation between water, air and the soil matrix with its ill-defined network of pores and fissures. Generally, it is represented as a volume per unit area and thus as an average depth (Figure 1). Initially, the root zone has been considered as the substrate for agriculture. However, in a wider context, for natural terrestrial ecosystems as a whole, the root zone storage is the buffer that the ecosystem created to provide continuous access to water. Although these processes are confined to a relatively thin layer, and only stores 0.13% of the total freshwater on Earth (McCartney et al., 2021), it is a critical factor in controlling land surface hydrological response, land-atmospheric moisture exchange, and biogeochemical processes (Zehe et al., 2019).

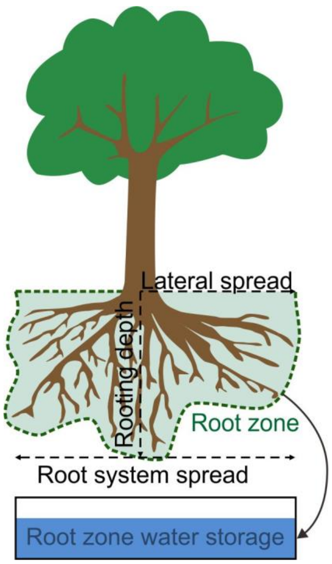

Figure 1. A sketch of the definitions of root zone and root zone water storage capacity (adapted from Tumber-Dávila et al., 2022)

The hydrological and land surface relevant magnitude of the ecosystem's root zone can be described by the root zone water storage capacity, i.e. S_{umax}, that represents the maximum subsurface moisture volume that can be accessed by the vegetation's roots (Gao et al., 2014; Stocker et al., 2023). Similar to artificial reservoirs designed by humans to bridge dry periods requiring investment of materials and energy, ecosystems also need carbon, energy and nutrients to develop their root zone water storage, as a buffer to overcome periods of drought. Reversely, S_{umax} is the maximum water deficit in the root zone, which occurs when all available moisture has been consumed after a critical drought period.

From a hydrological perspective, S_{umax} controls the partitioning of precipitation into infiltration to meet soil evaporation and plant transpiration demand and runoff generation (i.e., subsurface storm flow, percolation into groundwater, and discharge as baseflow). Thus, S_{umax} is the key parameter determining ecosystems' resilience to drought and runoff generation.

In Section 3, we will further clarify the definition of root zone and root zone storage capacity by comparing it with other "similar" terms in different disciplines.

3 The role of the root zone in the Earth system

Earth System Science is a rapidly emerging interdisciplinary endeavor aimed at understanding the structure and functioning of the Earth as an integrated, complex, and adaptive system (Steffen et al, 2020). Inspired by early work on the biosphere–geosphere interactions and novel perspectives such as the Gaia hypothesis (Lovelock, 1979), Earth System Science emerged in the 1980s following demands for a new 'science of the Earth'. Interestingly, in the latest conceptual model of the Earth System (Steffen et al., 2020), the root zone, as the interface among roots, soils, vegetation, lithosphere, freshwater, biosphere, and the production and consumption in human society, plays a central role, as the crucial element linking the Earth's geosphere and anthroposphere (Figure 2).

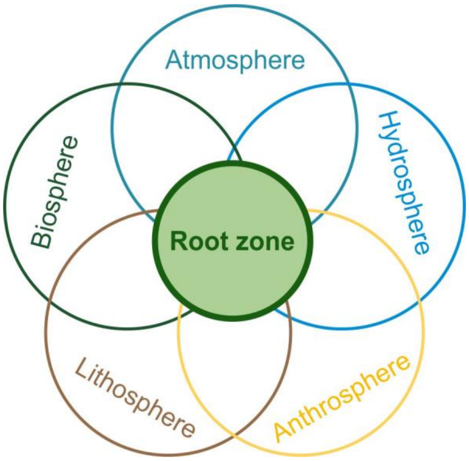

Figure 2. Root zone is the cross-section of biosphere, lithosphere, atmosphere, hydrosphere, and anthroposphere in the Earth system.

3.1 Root zone and biosphere

3.1.1 Functions of roots for plants

Roots are essential organs for plants to survive and reproduce in a great diversity of habitats. Plants rely on roots to uptake water and nutrients—two fundamental elements for plant performance; roots also anchor and support plants in the ground; roots store food made in the leaves by photosynthesis. Roots' sensing of local resources, such as water, nutrients and phosphate, enables better access to the heterogeneously distributed resources in the complex of pores and fissures in the substrate. Roots combined with a fully integrated vascular system were essential to the evolution of large plants, enabling them to meet the requirements of anchorage and the acquisition of water and nutrients (Boyce, 2005).

The root zone determines the resilience of ecosystems to droughts and climate change. Natural ecosystems optimally adjust their root systems to their environment, controlled mainly by climate and topography (Gao et al., 2014; Fan et al., 2017). The vegetation, i.e., the ensemble individual plants present at any moment, is a manifestation of their successful adaptation to past conditions - as otherwise these specific individual plants would not have survived and would not be there. This indicates that plants optimized (likely the results of long-term trial and error in evolution) their root-accessible water storage according to a cost minimization strategy, i.e., to meet canopy water demand as well as nutrient requirements with minimal carbon allocation to roots that in turn frees resources for above-surface growth that is needed to survive in competition for sunlight with other plants.

3.1.2 Rooting depth

There are many root traits, including root biomass, root turnover, root/shoot ratio, vertical root distribution, and maximum rooting depth (Figure 3a). Rooting depth is one of the most basic plant functional traits influencing ecosystem resilience, plant biogeography, pedogenesis, and carbon cycle.

Measuring rooting depth and other traits accurately is one of the most time-consuming and difficult activities in ecological and agricultural research, especially if it is a field study. The methodology also varies depending on the plant community. For example, the rooting depth of grass and agricultural crops is measured by collecting soil cores; while coarse roots of trees are estimated by allometric equations, and fine roots of trees are estimated by soil cores. A global rooting depth synthesis study covers 2200 world-wide root observations (Fan et al., 2017) reflects still a small sample compared to the number of trees 3.04 trillion (Crowther et al., 2015), and the even larger numbers of grass and agriculture crops. Thus, globally, we have very limited knowledge of the root system.

From a limited number of studies, we know that rooting depth has non-unique associations with climate and biome types (Jackson et al., 1996; Schenk, 2002). For instance, roots are shallow in boreal biomes on thinly thawed soils; roots of annual crops starting from seeds each season reach only shallow depths; and deep roots are found in arid, semiarid, and season-arid climates (Figure 3c). On average, woody plants such as trees and shrubs tend to be more deeply rooted than grasses and forbs. Plant species differ in root growth and distribution in the soil profile, especially under stress conditions. Interestingly, both the shallowest and the deepest roots are found in dry biomes (Fan et al., 2017).

Topography also has a large impact on rooting depth. Along a topographic gradient, root–water relation shifts systematically; on excessively drained uplands, the water table is deep or absent, and rooting depth is limited to infiltration depth/frequency. With the increase of Height Above the Nearest Drainage (HAND), rooting depth commonly increases with the increase of water table depth due to water limitation (Figure 3b; Fan et al., 2017).

Generally, climate, topography, and root genetic code determine rooting depth. However, accidental discoveries of >70-m-deep roots in wells and >20-m-deep roots in caves offer glimpses of the enormous flexibility of root response to its environment.

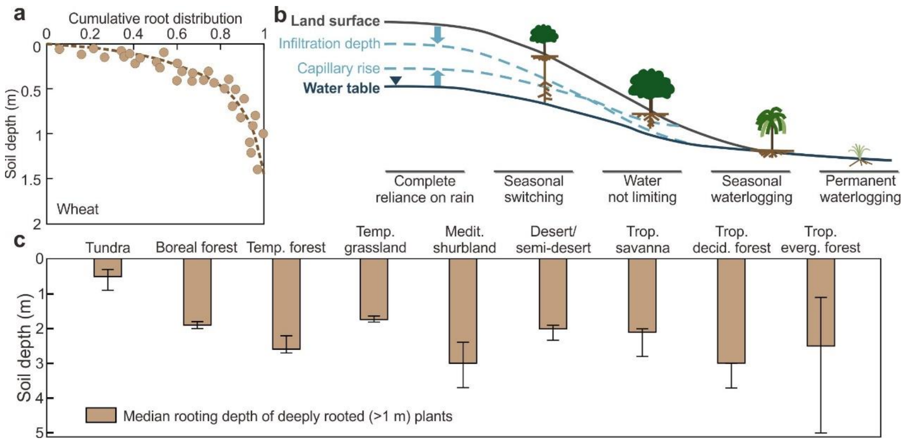

Figure 3. (**a**) Cumulative root distribution as a function of soil depth for wheat as an example (Fan et al., 2016). (**b**) Schematic of rooting depth and water table profile along a drainage gradient (Fan et al., 2017). (**c**) Comparison between estimated rooting depths of global vegetation types and sampling depths used in quantitative studies of vertical root distributions (Schenk and Jackson, 2002).

3.1.3 Root zone ≠ rooting depth

It is important to note that the root zone is not necessarily proportional to the rooting depth. While rooting depth only describes the vertical extension, the root zone reflects the root distribution over the entire profile. The root zone, moreover, accounts for lateral root extent and root density. Root distribution patterns in the soil profile are important determinants of the ability of plants to acquire nutrients and water necessary for growth. For example, an ecosystem covered by deep-rooting vegetation with roots with low density may have a smaller root zone than one covered by vegetation with shallow, high-density roots (Singh et al., 2020; van Oorschot et al., 2021). The vertical and lateral distribution and the root density are essential elements of the root zone. Even with detailed root distribution data, we cannot determine the root zone merely using root traits, due to the complex pores and fissures in soils and bedrock, and the complex hydrodynamic gradients, which will be discussed in Section 3.1.4 and 5.1.

3.1.4 Root zone ≠ rhizosphere

The rhizosphere is the zone around the root where microorganisms and processes important for plant growth and health are located (Hiltner, 1904; Hartmann et al., 2008). It includes roots, soil and the space in between, which is usually 1-4 mm (Kuzyakov and Razavi, 2019) (Figure 4). The plant root-soil interface is a dynamic region in which numerous biogeochemical processes take place driven by physical activity, including water and nutrients (Bengough, 2011). The rhizosphere supports microorganisms' growth (e.g., 10^7 - 10^{12} bacteria population in 1 g of rhizosphere soil) and thus stimulates biochemical processes in the root zone (Hinsinger et al., 2009). Root-associated microbial communities can strongly influence plant survival, phenology, and expression of functional traits (Kuzyakov and Razavi, 2019). Also, as much as half of this photosynthetic carbon can be lost from the soil by respiration within hours or days.

There are similarities between the rhizosphere and the root zone. Both zones are not stationary and not fixed. However, the rhizosphere is the soil volume directly around the living roots and usually covers just a few millimeters from the root surface. It is used to analyze direct interactions with microorganisms and to assess nutrient depletion zones. The root zone, however, is used in agronomy, hydrology, and land surface process issues, to assess the total amount of water and nutrients potentially available for plants. So in volume, there is a 2-3 orders of magnitude difference between the rhizosphere and the root zone. The rhizosphere is more like a biology and pedology concept on a micro-scale (Kuzyakov and Razavi, 2019), while the root zone is used for larger-scale hydrology and land surface studies in the Earth system.

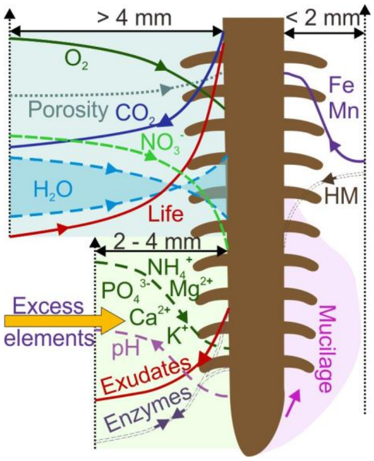

Figure 4 Generalization of rhizosphere extents and gradient types for the most investigated parameters: Gases, Root exudates, Nutrients and Excess elements, pH and Eh, Enzyme activities and microorganisms (from Kuzyakov and Razavi, 2019).

3.2 Root zone, lithosphere, and pedosphere

3.2.1 Roots as active agents of soil formation

Roots can sense the surrounding heterogeneous structure and avoid obstacles, both at the microstructural (volumes less than mm^3) and the macrostructural scales (Wang et al., 2020). Roots can open up the substructure by acting like a “wedge" (Pawlik et al., 2016). Roots promote rock weathering and play important roles in soil formation. Roots' associated fungi contribute to weathering and enlargement of rock fractures as well (Schenk, 2008).

Roots together with climate, topography, parent material and time, determine soil properties (Huggett, 2023). Roots prefer to grow in existing pore networks to penetrate deeper into soil and bedrock fissures. Due to the physical, chemical and biological activity of roots, the lithosphere has changed over time leading to increased root zone depth (Hetherington, 2019). Moreover, soils receive organic matter through the interaction with roots and fungi, exchanging carbon for minerals, fixing carbon underground and significantly altering soil properties (Cotrufo and Lavallee, 2022).

3.2.2 Root zone ≠ soil depth

The depth to bedrock forms the lower boundary of the soil, which determines soil depth. Although the root zone is strongly connected to the soil, it does not necessarily correlate to soil depth (Figure 5). For example, in most cases, especially in deep soil regions, such as the Loess Plateau in China, the root zone is limited to the most active layer of the topsoil, where most hydrological and biogeochemical processes occur, while the soil depth extends much deeper. In karst and other mountainous regions, the root zone does penetrate the bedrock and roots access water in fissures (McCormick et al., 2021). In arid climates, roots can even reach the deep groundwater; thus, in this case, the root zone also includes part of the groundwater (see Singh et al., 2020).

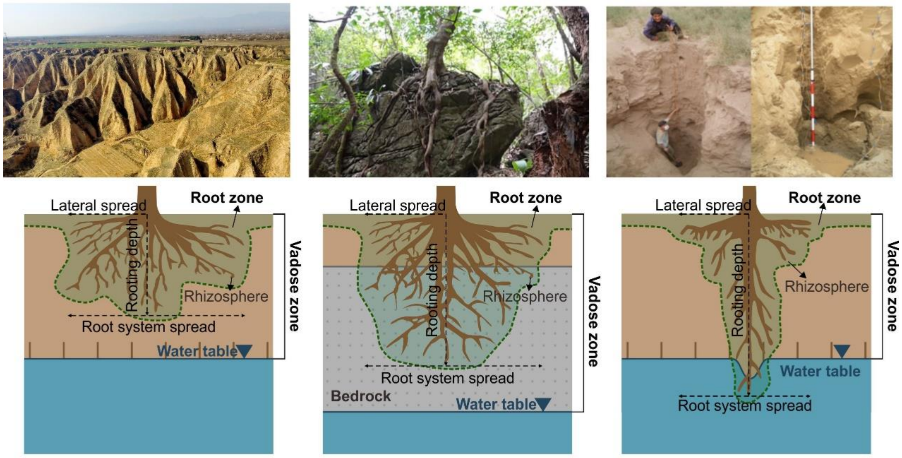

Figure 5 Root zone is different from soil depth.

3.2.3 Root zone ≠ critical zone

The definition of the critical zone is still controversial. The most widespread definition is from the National Research Council in the US (NRC, 2001): the critical zone is the near-surface layer of the Earth, including vegetation, soil, water, and rocks, all of which are essential elements for supporting life. Based on this definition, the critical zone ranges "from the canopy top to the base of the groundwater zone". There is high consensus on the top boundary of the critical zone, i.e., the top of the vegetation canopy. Its lower boundary, however, has many different versions, e.g., the base of the groundwater zone (NRC, 2001), the bottom of the weathering zone (Guo and Lin, 2016), the base of active groundwater (Fan, 2015), the storage of fresh groundwater (<50years old) (Gleeson et al., 2016). Whatever the definition of the critical zone, the root zone is part of it. Moreover, the root zone is the most active layer in the critical zone, including all elements of vegetation, soil, water, air, and rocks. It is the crucial element of the critical zone, connecting the full range from canopy to groundwater.

3.3 Root zone and hydrosphere

3.3.1 Root zone and hydrological processes

In the terrestrial water cycle, there is a hierarchy of processes. Starting with precipitation of moisture, it is first intercepted by vegetation and ground cover from which it can return to the atmosphere by evaporation or infiltrate into the soil and percolate to the root zone, where it is stored for plant utilization, and from where it can percolate deeper to the groundwater, or flow laterally to the drain. The water that does not infiltrate can flow overland to the drain. All these processes are to a larger or lesser extent dominated by the amount of water already present in the root zone. One can say that the root zone soil moisture is the key agent determining the partitioning of precipitation into evaporation, runoff, groundwater recharge and the build-up of storage. Over longer timescales, under equilibrium conditions, storage change may be disregarded, and precipitation goes to either runoff or evaporation, with the root zone exerting a strong control on this partitioning (Figure 6). Most land surface water fluxes (including evaporation and runoff) and water storages (including soil moisture, vegetation, and groundwater) are affected by the root zone. Consequently, the root zone plays a major role in regulating the land surface water budget, and much of this is due to the biophysical effects of plant roots on the surrounding soil (Bengough, 2011). The moisture flow from the land surface to the atmosphere through vegetation root water uptake (i.e. transpiration) is globally the largest water flux from terrestrial ecosystems at about 60-70% of total evaporation (Schlesinger and Jasechko, 2014; Coenders-Gerrits et al., 2014; Lian et al., 2018). This flux is largely responsible for the recycling of moisture in the atmosphere where about 60% of all precipitation originates from terrestrial evaporation (Van der Ent et al., 2010)

For runoff generation, there are two classical mechanisms, i.e., saturation excess flow and infiltration excess flow (Beven, 2012). Root zone characteristics determine both. Saturation excess flow is the dominant mechanism in humid catchments. Based on this theory, there is no runoff generation when the root zone still has a moisture deficit, i.e. root zone moisture is below a critical threshold (so called field capacity). Once the root zone moisture crosses this threshold, outflow pathway becomes activated, and runoff is generated. This mechanism is also named fill-and-spill (McDonnell et al., 2021) or store-and-pour (Phillips, 2022). Due to landscape heterogeneity (mainly topography), the runoff threshold has a spatial distribution function so that saturation and runoff generation does not happen all at the same time in an entire catchment. Usually, riparian zones (close to the drain) are saturated first, where saturation excess flow first occurs. Subsequently, the contributed areas expand with the increase of precipitation amount and root zone moisture. Thus, the saturation excess flow mechanism is also called the variable contribution area theory. The concept can be functioned as:

$$Q(t) = f(P(t), S_u(t), S_{umax}, \beta) \quad (1)$$

where $Q(t)$ is the runoff generation in time *t*; *P* represents precipitation, S_u represents root zone moisture; S_{umax} represents root zone storage capacity; β represents the spatial distribution function of the saturation threshold (Gao et al., 2017).

In contrast to saturation excess flow, infiltration excess flow occurs mostly in arid climates. Based on this theory, the temporal and spatial dynamic of infiltration excess flow is determined by the

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relationship between precipitation intensity and infiltration capacity. When rainfall intensity is larger than infiltration capacity, runoff generation occurs; otherwise, all rainfall goes into infiltration without runoff generation.

$$Q(t) = f\left(P(t), f_c(t)\right) \tag{2}$$

where P is precipitation intensity, f_c is infiltration capacity, including matrix infiltration capacity, and preferential infiltration capacity.

Traditionally in hydrology, the infiltration process is considered to be dominated by matrix flow, with the assumption that soil texture controls hydraulic properties and infiltration capacity (Beven, 2021). However, mounting evidence has revealed that preferential flow transmits free water quite rapidly to the subsurface, dominating water movement even in arid regions (Liu et al., 2012; Gao et al., 2023). Plant rooting system in water-limited environments correlates strongly with infiltration capacity, velocity, and depth (Schenk & Jackson, 2002b; Schenk, 2008). Infiltration recharges the root zone moisture through preferential patterns, and additional water can generate runoff or percolate to the groundwater. Moreover, recent studies revealed that mucilage exuded from roots and rhizosphere bacteria is critical in the formation of liquid bridges at the root–soil interface, influencing mechanical stability and hydraulic properties in the root zone (Bengough, 2011). Root zone properties are essential in determining infiltration capacity and infiltration excess flow generation for both matrix and preferential flow.

At landscape scale, topography emerges as a determining factor on the root zone size and runoff generation mechanisms. Usually, saturation overland flow occurs on wetlands and riparian areas, subsurface stormflow occurs on hillslopes, and infiltration overland flow usually happens on plateaus or terraces (Savenije, 2010; Gao et al., 2014; Gharari et al., 2014). In summary, regardless of saturation excess flow (also called variable contribution area) or infiltration excess flow, the root zone plays a determining role in both hillslope and catchment hydrology.

The root zone also controls percolation to groundwater (Collenteur et al., 2021). In most conditions, groundwater recharge and runoff generation are highly related, since runoff is generated from groundwater in most circumstances (Ali et al., 2011). The root zone also influences evaporation and transpiration from groundwater. Soil surface and root zone drying are mitigated by upward capillary flow from the subsurface. The capillary rise sustains evaporation during dry spells and decreases groundwater recharge on a longer timescale. A widely observed phenomenon is the diurnal cycle of both streamflow and groundwater table fluctuation, mostly in arid and semi-arid catchments (Lundquist and Cayan, 2002; Wang et al., 2014; Yue et al., 2016). Vegetation, mostly in riparian areas, directly taps groundwater for transpiration, daytime root water uptake causes water tables to decline during the day, while water tables recover at night when transpiration essentially ceases (Yue et al., 2016). This shows the direct hydraulic link between the root zone moisture, the groundwater and the runoff in streams,

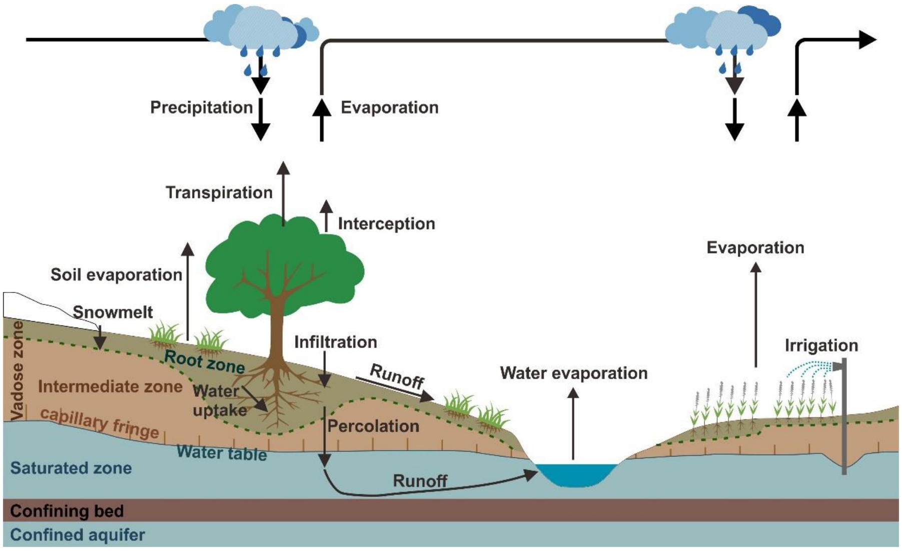

Figure 6. Schematic diagram of the root zone in terrestrial hydrological processes and atmospheric moisture cycling.

3.3.2 Root zone ≠ vadose zone

The vadose zone is the unsaturated area, including the root zone, transition zone, and capillary fringe above groundwater. From a hydrology perspective, the vertical profile of the critical zone can be divided into different layers: canopy, litter layer, root zone, water transition zone, unconfined groundwater, and confined groundwater. The most active layers in the critical zone defining rainfall partitioning and related hydrological processes include the canopy, litter layer, and root zone. Globally, the vegetation interception storage capacity of terrestrial ecosystems is about 1-2 mm, estimated by remotes sensing LAI data (De Roo et al., 1996). The litter layer storage capacity differs in different ecosystems, but it is likely to increase the total interception storage capacity to around 2-5 mm (Shi et al., 2004). For determining the root zone storage capacity of ecosystems, the mass curve technique appeared to work well locally and globally (Gao et al., 2014; Wang-Erlandsson et al., 2016), whereby use was made of ERA-5 evaporation data, resulting in a global average root zone storage capacity of approximately 180 mm. Hence, the root zone storage capacity is significantly larger than the interception and litter layer storage capacities. It is worth noting that soil evaporation in well vegetated regions is negligible due to the shielding effect of the canopy and litter layer. In sparsely vegetated regions, e.g., deserts, soil evaporation may play a more important role. Distinguishing the topsoil evaporation and the root zone transpiration needs more complementary information, e.g., using isotope data. Both large-scale isotope measurements and modeling studies confirmed that soil evaporation is around 6% of total evaporation globally (Wang-Erlandsson et al., 2014; Good et al., 2015). Hence, the topsoil evaporation is significantly less important than evaporation from the root zone.

Beneath the root zone, the transition zone is the layer between the lower limit of the root zone and the upper limit of the capillary fringe, which is thick where the depth to the water table is deep and may be absent where the water table is at or near the surface. This transition zone forms a

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transport belt for percolation from the root zone to groundwater system, without water phase changes, and does not have an impact on the land surface water balance. The percolation through the transition zone recharges the groundwater and will be discharged eventually as runoff under natural conditions. The deep confined groundwater has a limited connection to surface processes and is not considered in surface runoff calculations in most cases. Hence, the root zone, as the active layer within the vadose zone, plays the dominant role in catchment hydrology, determining how catchments respond to precipitation.

3.4 Root zone and atmosphere

3.4.1 Root zone and land surface processes

The importance of the root zone on land surface and climate modeling is widely acknowledged (Milly and Dunne, 1994). The moisture condition in the root zone is essential for water fluxes in land-atmosphere interactions, mostly by increasing atmospheric water vapor through root water uptake and transpiration. The contribution of transpiration to total land evaporation is regulated by the interplay between the atmospheric water demand and the soil moisture within the reach of vegetation's roots. Inversely, vegetation and land cover regulate the exchanges of root zone water, energy and carbon with the atmosphere. Recent studies emphasized the potential of harnessing climate-controlled root zone parameters to improve water flux simulations by the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL) land surface model (e.g., van Oorschot et al., 2021).

The root zone is both affected by and affecting the Earth's climate (Jackson et al., 1996). Compared with soil evaporation and canopy interception, vegetation can use deeper root zone water for transpiration, allowing for long-term climate memory over longer distances (van der Ent and Savenije, 2011). Land use impacts large scale moisture recycling and land use change in one region can impact the precipitation in faraway regions downwind (van der Ent et al., 2010; Wang-Erlandsson et al., 2018).

3.5 Root zone and cryosphere

The frontier of climate change studies is the terrestrial cryosphere, including glaciers, snow cover and frozen ground. Glacier and bare rock/soil covered cold regions do not have vegetation cover thus without root zone. Root zone and cryosphere have connections mostly in vegetation-covered frozen ground. Snowfall and snowmelt, as an important cryospheric element, have significant impacts on root zone hydrological processes in permafrost, with a time delay from snowfall on the ground to snowmelt into the root zone. Snow cover as an isolation layer, reduces soil evaporation, and likely increases soil temperature with a thick snow depth. Snow melt, in addition to rainfall, increases infiltration, plant available water, plant growth, and runoff generation. In cold regions, it is necessary to consider the effects of snowmelt on root zone water storage and the soil freeze–thaw processes on hydrologic connectivity (Gao et al., 2020, 2022; Wang-Erlandsson et al., 2016; Zhao et al., 2016; Dralle et al., 2021). The interaction between the root zone and the cryosphere, especially snow cover and frozen soil, attracts increasing attention and research interest (Gao et al., 2018; Leng et al., 2023) but still lacks systematic studies.

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3.5.1 Root zone ≠ active layer in permafrost

In permafrost regions, the active layer, experiencing seasonal freeze/thaw processes, determines the maximum thawing depth. Roots cannot grow in the ice layer and permanent frozen layer. The rooting depth of deeper-rooting species, if present, is restricted to the active layer (the upper layer of soil that thaws annually) because of the impermeability of the permafrost (Blume-Werry et al., 2019). In climate change, when the permafrost underneath the active layer thaws, previously unoccupied soil volumes become available for plant roots. Permafrost thaw leads to a larger active layer and deeper groundwater table, which likely influence rooting depth and distribution. Changes in rooting patterns and dynamics, as a direct response to permafrost thaw or indirectly through changes in vegetation composition or soil moisture, have the potential to influence carbon cycling in cold regions strongly (Wang et al., 2020).

4 Root zone in the Anthropocene

4.1 Climate change

Climate, as the upper boundary of the root zone, has the dominant impact on root zone dynamics. Root growth is highly dynamic and responds quickly to changes in environmental conditions. The time between photosynthesis and the transfer of carbon from leaves to roots and soil organisms is fast, taking hours in grassland or days in forests. Changes in the root zone are generally cumulative, which may be introduced by slow, gradual or abrupt changes.

Previous work demonstrated that root zone storage capacity (S_{umax}) varies spatially in response to climatic conditions (Kleidon and Heimann, 1998; Gao et al., 2014; Wang-Erlandsson et al., 2016; Stocker et al., 2023). It is, therefore, not implausible to assume that S_{umax} also varies temporally in response to climate change. In the absence of longer time series of observed historical ecological data, the 'space-for-time' assumption is a potential option to infer temporal ecological trajectories from available spatial patterns (Singh et al., 2020). By comparing S_{umax} with aboveground tree cover in several transitions across tropics and subtropics, Singh et al. (2020) found that in tropical forests, with increased water stress, ecosystems tend to increase their S_{umax} and reduce tree cover. Once the ecosystem passes across the tipping point, i.e. S_{umax} of 400 – 750 mm, and tree cover of 30-40%, rainforests in the Amazon appear to transition to savanna. This insight may be a manifestation of an ecohydrological adaptation strategy, which offers potential for prediction under future climate change.

At basin scale, Bouaziz et al. (2022) found that vegetation had adapted to climate change by increasing its root zone storage capacity to offset the more pronounced hydro-climatic seasonality in the Meuse basin. The increased vegetation water demand under global warming results annually, and on average, in less streamflow, more evaporation and less groundwater recharge. At global scale, Gao et al. (under review) analyzed observation-based ERA-5 reanalysis data to find that the global average rootzone water storage capacity has increased by 8% over the past four decades (1982-2020), in response to intensifying drought. The widespread increase of S_{umax} was further validated by using the dynamic identifiability analysis (DYNIA) algorithm with a five-year moving window to explore the dynamics of the S_{umax} parameter, forced by the observed catchment hydrometeorological data of the USA (Liang et al., under review). At landscape scale, local topography and groundwater also matter. In response to declines in the water table, rapid root growth (up to 15 mm/d) toward the water table has been observed for desert phreatophytes vegetation (Orellana et al., 2012; Kuzyakov and Razavi, 2019).

The net effect of the presence of plants with roots on land is to draw CO_2 out of the atmosphere, which has a major effect on climate. Root zone dynamics are also important for carbon sequestration, such as predicting how plants respond to elevated CO_2 under climate change (Nie et al., 2013). Of carbon storage alternatives, root zone carbon has the largest uncertainty, with great influence on carbon neutrality and sequestration, which still needs further experimental and modeling studies (Friedlingstein et a., 2022).

4.2 Agriculture

Most agricultural activities are happening in the root zone, including but not limited to irrigation, fertilization, tilling, non-point source pollution, and salinization. Root zone management is essential for food production and food security. Originally, the term "root zone" has been used in agronomy, e.g., to assess the total amount of water and nutrients available for plants. Ploughing as an important agriculture management practice, which greatly changes and even determines the root zone depth. The plough pan, distributed commonly from 15 to 30 cm beneath the soil surface, caused by long-term cultivation, is formed under the root zone with a high clay content (Li et al., 2019). This relatively impermeable layer limits water percolation and constrains root growth in the relatively small soil layer above the plough pan. In such cases, it is indeed the moisture holding capacity of the topsoil that determines the root zone storage capacity.

In cropland, where irrigation provides an extra water supply to the root zone during dry seasons, the root zone water storage capacity is often smaller than under natural conditions with similar climate conditions (Xi et al., 2021; Hauser et al., 2022; van Oorschot et al., 2023). Due to irrigation (not considering climate change), rooting depth was reduced by 5%, or ~8 cm, or loss of ~11,600 km^3 of rooted volume (Hauser et al., 2022). In a global scale study, when considering irrigation as an extra water supply, S_{umax} in cropland was found to consistently decrease (van Oorschot et al., 2023).

Agricultural activities also dramatically changed root zone biogeochemistry cycles. All living things need nitrogen (N) and phosphorus (P) to make amino acids, proteins, and DNA. However, most of the nitrogen on Earth is in the atmosphere, in the form of N_2, which cannot be directly used for most plants and all animals; and phosphorus is supplied by physical and biological rock weathering, which is an extremely slow process. Thus, in natural terrestrial ecosystems, N and P are often the most limiting nutrients for productivity. Chemical fertilizer revolutionized this limitation, changing from nutrient scarcity to overloading, resulting in a series of environmental issues, e.g., soil hardening in the root zone, groundwater contamination, surface water eutrophication, and phosphate resource depletion (UNEP, 2019; Yao et al., 2020; Edixhoven et al., 2014). Thus, agricultural root zone management is a pivotal issue for food security, human health, water resources management, and environmental protection (Gu et al., 2023).

4.3 Nature-based solutions

4.3.1 Large-scale ecological projects

Large-scale land cover change will dramatically change hydrology, land surface processes, and biogeochemistry cycle, between which the root zone is the crucial link. For example, intensive deforestation greatly reduces root zone water storage capacity (Hrachowitz et al., 2021), requiring over ten years to recover (Nijzink et al., 2016). In regions experiencing woody encroachment, roots are deepening by ~38 cm compared to previous dominant vegetation (Hauser et al., 2022).

The root zone plays an essential role in evaluating the effects of large-scale ecological projects. For instance, the “grain-to-grass” and “three norths afforestation projects” in China, have been greatly beneficial for soil and water retention, biodiversity conservation, and carbon sequestration (Chen et al., 2019; Li et al., 2021). But these projects still face great challenges in water management of these arid regions, where severe competition exists between society's water demand and ecosystem services (Feng et al., 2016). Moving from blue water management to integrated water resources management, means bringing both blue- and green-water, surface and groundwater, in the same framework (Falkenmark, 2000). Root zone moisture forms the essential link between land surface fluxes, water resources, soil erosion, and carbon sequestration, determining the success and sustainability of these grand projects (Sun et al., 2020).

4.3.2 Water-soil conservation and landslide prevention

Afforestation is regarded as an effective nature-based solution for water-soil conservation and flood mitigation. Forests have higher evaporation due to deep roots and large biomass. Higher evaporation results in higher soil water storage capacity to store more rain water for dry periods. For example, afforestation in the Yangtze River basin was expected to reduce flood risk by increasing its root zone water storage capacity as "green reservoirs". However, there has been a long dispute about the efficiency of forests in flood control, especially after the megaflood in Changjiang in 1998. Interestingly, in Thailand, Sriwongsitanon et al. (2011) found that forests have a large impact on small floods but no significant impact on extreme floods.

From a long-term evolutionary perspective, rooting increases weathering and soil formation. On the short-term, roots' anchoring effect holds soil in place, reduces the erosion rate, increases slope stability, and prevents landslides and debris flow catastrophes (Vannoppen et al., 2017). Forest communities are considered to effectively minimize erosional processes and support hillslope and riverbank stability (Pawlik et al., 2016). They also effectively contribute to soil strength, reducing probability of shallow land sliding. The reduced sediment flow generation by roots also has basin scale impacts on downstream river geomorphology. For example, rivers were changed from braided river channels to predominately meandering river channels due to the stabilizing effects on riverbanks that rooting systems provide (Ielpi et al., 2022). It changes both suspended and bed load sediment fluxes, which has remarkable effects on infrastructural security and service life of dams, dikes, and water uptake facilities (Cao et al., 2023).

4.3.3 Sponge city

Human alterations of the root zone have increasingly become pervasive and long-lasting, which is particularly true in urbanized areas. Urbanization alters land surface by changing from permeable to impermeable. This significantly changes the root zone hydrological process and land surface energy budget, intensifying urban inundation and urban heat island effect (Fletcher et al., 2013). There is also an increasing interest in using vegetation to manage catchment and regional hydrology (Palmer et al., 2015), especially in the urban environment, as exemplified by the

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"Sponge City initiative" in China (Xia et al., 2017). The root zone is the largest and most widespread "sponge" in forests and grassland at large scale, whereas green roof and garden provide a "sponge" at city and block scale. Increasing S_{umax} has potential to improve flood prevention, water purification, relieving heat island effect, and aesthetic value in the urban environment.

4.4 Planetary stewardship

As the key linkage between the natural geosphere and the anthroposphere (Figure 1, and Steffen et al., 2020), understanding the root zone has broad relevance to planetary stewardship, such as green water footprint, integrated water resources management, and carbon sequestration (Wang-Erlandsson et al., 2022). The root zone plays a key role in partitioning precipitation into the invisible green water (used for terrestrial ecosystem) and visible blue water (usable for human society) (Falkenmark, 2000). The root zone is one of the most manageable variables in the terrestrial water cycle and land system. Almost all human activities have impacts on the root zone, like agriculture, urbanization, deforestation/afforestation, landuse change, and fertilization. Proper root zone management is essential to keep both green and blue water within safe planetary boundaries for Earth system resilience (Wang-Erlandsson et al., 2022; Stewart-Koster et al., 2023). Root zone management is essential for numerous global sustainability development goals (SDGs), including but not limited to SDG1 (no poverty), SDG2 (zero hunger), SDG3 (good health and well-being), SDG6 (clean water and sanitation), SDG11 (sustainable cities and communities), SDG13 (climate action), and SDG15 (life on land).

5 Root zone estimation approaches

5.1 Root zone water storage capacity ≠ rooting depth × soil water holding capacity

In most Earth system models, root zone storage capacity is obtained by combining rooting depth with soil water holding capacity derived from soil texture data. The soil water holding capacity is obtained in the laboratory and defined as the amount of water held by the soil between field capacity and permanent wilting point, which is available for plant water use (van Oorschot et al., 2021). In this type of models, the water exceeding field capacity is drained under gravity; and below wilting point, vegetation starts to wilt, leading to plant mortality.

However, we argue that this traditional perspective, which believes that the sum of the parts is equal to the whole, is problematic. Firstly, this type of method usually lacks detailed observations of root density and vertical and lateral distribution, which has large uncertainty, and, in most cases, lacks observations and heavily relies on parameter calibration. But even considering the root density and vertical and lateral distribution, we cannot obtain reliable root zone water storage capacity, from only one observation. Emerging ecohydrology studies revealed that hydraulic lift is important for trees in the nighttime redistribution of water from wetter soil deeper in the soil profile through roots to drier soil closer to the surface (Bleby et al., 2010; Nadezhdina et al., 2010). This phenomenon is observed for individual trees and measured in exchanging water and nutrients among neighboring trees (Hafner et al., 2021). Hence, it is extremely difficult if not impossible to define the exact shape of the root zone of an ecosystem by a reductionist approach

(Figure 7). The root zone consists of a gradient in chemical, biological, and physical properties that change radially and longitudinally along the root (McNear, 2013; Kuzyakov and Razavi, 2019). For example, the presence of arbuscular mycorrhizal fungi is known to enhance plant water uptake, particularly important during water-stressed periods (Augé, 2001), by boosting root growth and potentially also through direct water acquisition (Püschel et al., 2020). This complex of pores and fissures in the substrate, extending both laterally and in depth, with complicated extents and gradients of water and nutrients, cannot be simulated by the mechanical combination of rooting depth and soil properties (Figure 7).

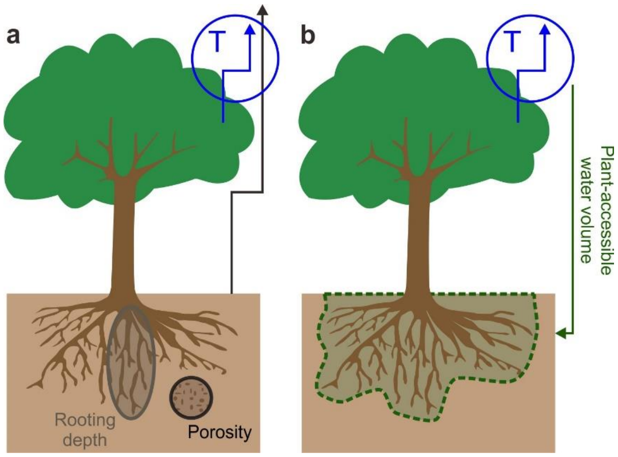

Figure 7. The reductionist (**a**) and holistic (**b**) perspective. (**a**) The reductionist perspective estimates root zone storage capacity and transpiration based on rooting depth and soil properties, which is a stationary view, mostly based on soil information. (**b**) The holistic perspective estimates root zone storage capacity and transpiration based on plant water demand, which is a dynamic view, mostly based on climate and plant adaptation.

5.2 Holistic perspective

Holistic perspectives view the root zone as an integrated and living system leading to self-organization and fractal patterns. Reductionist modelers ask the question of "How deep is the root zone?". Holistic modelers ask the questions "What is the size of the root zone?" and “How much moisture can it buffer?”.

The inverse modelling approach uses land surface water and energy fluxes, such as precipitation, evaporation, and radiations, and biomass observation, such as net or gross primary production, to derive root zone processes with different parameterizations (Kleidon, 2004). The mass curve technique (MCT), as an inverse model, is an observation-based approach to estimate root zone processes, based on the land surface water budget (Gao et al., 2014; Wang-Erlandsson et al., 2016). Catchment and global scale studies have revealed that ecosystems tune to a drought period with 10–40-year return periods depending on the type of ecosystem (evergreen, deciduous, grassland, etc.). Successful applications have been made by Gao et al. (2014), Nijzink et al. (2016), Wang Erlandsson et al. (2016), Sriwongsitanon et al. (2016), De Boer-Euser et al. (2019), Mao and Liu (2019) and Bouaziz et al. (2022), which show large diversity in hydrological fluxes globally, which cannot be obtained by traditional reductionist methods.

This powerful holistic method allows hydrologists and ecologists to derive underground processes by large scale observations from space (Kühn et al., 2022). Another interesting implication is by McCormick et al. (2021), who found that the water storage capacity of the topsoil is insufficient to explain evaporation in dry seasons in many areas across the USA, and, therefore, rock moisture is a critical component of terrestrial water. The MCT method, on the other hand, allows us to quantify this amount of water use from rock fissures (Lapides et al., 2023).

At landscape scale, the spatial distribution of S_{umax} is mostly determined by topography (Gao et al., 2019). Moreover, topography plays an essential role in determining runoff generation mechanisms, such as by saturated overland flow in wetlands, subsurface storm flow in hillslope, and infiltration excess overland flow in terrace (Savenije et al., 2010; Gharari et al., 2014).

The holistic perspective also needs holistic observations, including land surface fluxes like lysimeter, eddy covariance, and satellite remote sensing (Gao et al., 2014; Wang-Erlandsson, 2016; Kühn, 2022). Weighing lysimeter provides a unique equipment to quantify the water balance in the root zone (Seneviratne et al., 2012), especially, when comparing non-vegetated and vegetated systems, demonstrating the role of vegetation dynamics in controlling the water cycle (Scanlon et al., 2005). Satellite remote sensing provides more spatially and temporally extensive data about land surface water fluxes, such as precipitation and evaporation. Remote sensing also provides direct surface moisture measurement, such as SMAP and SMOS. However, satellites can only measure water in a few centimeters of the topsoil. Root zone moisture was then derived from surface moisture by the soil hydraulic model (Entekhabi et al., 2010). Interestingly, Sriwongsitanon et al. (2016) found that the normalised difference infrared index (NDII) is a better indicator for root zone moisture, which means that vegetation itself is a holistic indicator of root zone moisture conditions rather than an obstacle for remote observation that needs to be removed.

Comparing the reductionist with the holistic approach, it is interesting that although the holistic method is much simpler, its performance is even better than the most complex reductionist approach in runoff modeling (Mao and Liu, 2019; Wang et al., 2021), especially in ungauged basins (Hrachowitz et al., 2013), and evaporation flux simulations by land surface models (van Oorschot et al., 2021). The holistic method has also been used in the widely used dynamic vegetation model, i.e., LPJ-GUESS, by the inclusion of bedrock vadose zone, to improve its representation of storage and hydrology (Lapides et al., 2023). Considering plant's water use from bedrock improved evaporation estimation, especially in seasonally dry regions. Moreover, the holistic model is much easier to be coupled with biogeochemistry processes, especially in the sense that conceptual models are the dominant approach to simulate the carbon, nitrogen, and phosphorus fluxes.

6 Summary and future outlook

The root zone is the crucial element linking multi-spheres of the Earth surface system, including biosphere, lithosphere, hydrosphere, atmosphere, cryosphere, and anthroposphere. Although many disciplines are studying the root zone from different angles, this is not yet done in a systematic way. This study explored the differences and linkages between the root zone and other terminologies. For example, the root zone does not equal rooting depth or rhizosphere in biology and ecology. In pedology and lithology, the root zone is not equal to the soil depth or critical zone. In hydrology, the root zone is not equal to the vadose zone. In atmospheric science, the root zone storage capacity is not equal to the product of rooting depth with soil water holding capacity. Clarifying the terminology is essential for future studies. Furthermore, we discussed the root zone in the Anthropocene, including climate change, agriculture, nature-based solutions, and planetary stewardship. In the end, we discussed the traditional reductionist perspective to understand and model root zone, and we proposed to move forward to a holistic perspective to root zone in Earth system science.

We argue that more experiments and measurements in diverse climates and landscapes, especially holistic perspective methods, such as rhizobox and field control experiments (Nie et al., 2013), and long-term lysimeter measurements (Scanlon et al., 2005), are especially needed to get a deeper understanding of root zone patterns and dynamics. For example, rhizobox experiments interestingly demonstrated that precise root distribution information is unnecessary to estimate water budgets correctly (Maan et al., 2023). The booming development of root microbiome studies in ecology, can greatly enhance our understanding of the rhizosphere biotic processes in the root zone, its importance for the entire ecosystem, and even its impacts on the large scale biogeochemistry cycle (McNear, 2013).

For modeling, the flexibility of plant roots and their ability to adapt to the environment, is still not properly incorporated in land surface and dynamic vegetation models. Reductionist modeling is still the mainstream methodology in Earth system models, but holistic modeling of the root zone has large potential for simpler and more realistic large scale simulation. For example, Singh et al. (2020) provided a spatial transient of S_{umax} changes as a function of climate. Based on space for time exchange, this paradigm can be used to predict the dynamic of belowground and aboveground biomass variations with climate change. Moreover, the holistic modeling approach allows us to involve more physical laws in hydrological modeling, not only the Newtonian approach but also evolution theory and energy efficiency, with the Carnot limit as its upper constraint (Savenije, 2023). Additionally, we need a better representation of root zone biogeochemistry processes, including carbon, nitrogen, phosphate, pollutants, and microbial communities for broader implications in Earth system science. Finally, we need to consider the impacts of human activities on the root zone in Earth System Models (ESMs) for better root zone management and relevant decision-making.

Essential in the holistic approach is the ecosystem perspective. The ecosystem is the active agent that manipulates the environment to sustain its survival. In doing so, it adjusts the substrate on which it lives, creating a favorable hydrological, geochemical, and biological foundation for its sustenance. Analysis of what the ecosystem has done over time to create conditions for survival and rejuvenation holds the key to understanding hydrological processes and can help to predict hydrological behavior under future climates.

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