Root zone in the Earth system

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Abstract: The root zone is a vital part of the Earth system and a key element in hydrology, ecology, agronomy, and land surface processes. However, its definition varies across disciplines, creating barriers to interdisciplinary understanding. Moreover, characterizing the root zone is challenging due to a lack of consensus on definition, estimation methods, and their merits and limitations. This Opinion paper provides a holistic definition of the root zone from a hydrology perspective, including its moisture storage, deficit, and storage capacity. We demonstrate that the root zone plays a critical role in the biosphere, pedosphere, rhizosphere, lithosphere, atmosphere, and cryosphere of the Earth system. We underscore the limitations of the traditional reductionist approach in modeling this complex and dynamic zone and advocate for a shift towards a holistic, ecosystem-centered approach. We argue that a holistic approach offers a more systematic, simple, dynamic, scalable, and observable way to describing and predicting the role of the root zone in Earth system science.

1 Introduction

Plant roots developed before leaves during the Devonian Period, 416 to 360 million years ago

(Kenrick and Strullu-Derrien, 2014). The development of root systems was a critical biological innovation that enabled land plants to spread and colonize the continental interior. Before this development, plants were limited to areas immediately adjacent to bodies of water due to their simple rhizoid-based rooting systems (Smart et al., 2023). Roots acted as pioneers of biological activity, representing a definitive line between sterile sediments and living soils. Fossil evidence indicates that deeper soils and larger plants appeared almost simultaneously (Kenrick and Strullu-Derrien, 2014).

There is a positive feedback between soils and plants, mediated by roots. Larger plants generally require more stable and deeper soils, while plant roots contribute to soil formation. The rapid expansion of terrestrial plants was largely enabled by newly developed rooting systems. Roots promoted physical, chemical, and biological rock weathering and increased terrestrial photosynthesis capability (Maeght et al., 2013), which significantly reduced atmospheric CO_2. This reduction likely triggered the ice age and mass extinction in the late Devonian (Smart et al., 2023).

Thus, the evolution of plant root systems not only influenced the local soil microenvironment and individual plant life cycles but also affected the weathering of the lithosphere, the formation of the pedosphere, and atmospheric compositions. The initial appearance of rooting systems transformed the entire biosphere and the abiotic environment on the planet (Hetherington, 2019).

In recent decades, the root zone has received increasing attention from various disciplines, including hydrology, ecology, agronomy, biology, soil physics, atmospheric science, and landscape engineering. Despite this growing interest, there remains a lack of synthesis on the basic concept of the root zone, especially within the context of Earth system science. The root zone is arguably the least understood portion of the ecosystem that controls land-surface processes (Wang et al., 2018). Therefore, there is an urgent need to clarify its definition and bridge the knowledge gaps between traditional disciplines.

This study has the following objectives:

1. Provide a definition of the root zone.
2. Propose a perspective of the root zone as a living, evolving, adapting, and essential part of the Earth system.
3. Advocate for a shift from the traditional reductionist approach towards a holistic, ecosystem-centered perspective of root zone hydrology in Earth system science.

2 The definition of root zone

2.1 Root zone

The *Root zone* is the upper part of the subsurface that supports vegetation rooting (Sprenger et al., 2019), where water, air and nutrients are available to sustain plants (see Figure 1, and Rodríguez-Iturbe & Porporato 2004). It typically extends through the unsaturated soil or parts thereof and may also reach the groundwater (Fan et al., 2017) or penetrate weathered bedrock (McCormick et al., 2021). The root zone is a hydrologically active layer, replenishing with water during wet periods and supplying ecosystems with water to survive droughts in dry periods. It controls the partitioning of precipitation into infiltration, soil evaporation, plant transpiration, percolation to groundwater and runoff (including surface runoff and subsurface storm flow) (e.g.: Guswa, 2010; Lazarovitch et al., 2018).

The root zone is a cross-scale concept, applicable at various scales including (Delcourt and Delcourt, 1988; Bloeschl and Sivapalan, 1995):

- Small scale (1~10^6 m^2, plot, landscape, hillslope and sub-catchment scales),
- Meso-scale (10^6~10^{10} m^2, catchment scale), and
- Large scale (above 10^{10} m^2, river basin and continental scales).

2.2 Root zone water storage and root zone water deficit

The root zone acts as a buffer, ensuring continuous access to water for an ecosystem to bridge dry periods. Its shape, hydrological gradients, as well as internal water fluxes and processes, are highly dynamic and complex. The interaction of plant roots, soil particles, bedrock fissures, water, nutrients, and micro-organisms create an intricate system (McDonnell et al., 2007). From an ecosystem-centered hydrology perspective, the complex root zone can, reflecting a "Darwinian" approach (Harman and Troch, 2014), be viewed as a dynamic system within a living organism (Savenije and Hrachowitz, 2017; Savenije, 2024).

Water storage in the root zone can be conceptualized as a volume of water per unit area, represented as an average depth (e.g. in mm) (see Figures 1 and 4). The water deficit (S_d) is defined as the difference between the maximum water volume and the actual root zone water storage at any time $S(t)$. Water deficit and water storage are two sides of the same coin. During rainfall events, the root zone wets up and refills as water is retained. Once the root zone moisture exceeds its water retention capacity, excess water drains off by recharge to the groundwater (triggering groundwater flow), or by lateral preferential flow, or as overland flow (by saturation excess or infiltration excess) directly to the stream. These processes may occur at the same time (McDonnell, 2013). In dry periods, ecosystems rely on the water stored in the root zone, leading to an increasing water deficit.

2.3 Root zone water storage capacity (S_{Rmax})

The root zone storage capacity (S_{Rmax}) is the maximum volume of water stored in the subsurface that can be accessed by roots and that the root zone can contain, to allow plants to overcome critical drought periods (Rodríguez-Iturbe & Porporato 2004; Gao et al., 2014a; Klos et al., 2018; Stocker et al., 2023). S_{Rmax} is the core property of terrestrial hydrological systems and therefore also a key parameter in process-based hydrological models, determining the partitioning between drainage and evaporative fluxes. From a soil hydraulic perspective, S_{Rmax} represents the water volume stored in the subsurface between permanent wilting point and field capacity and that is within reach of roots. In other words, S_{Rmax} is equivalent to the maximum water deficit in the root zone, which defines the volumetric extent of the root zone (Gao et al., 2014a; Lapides et al., 2024). This concept can be likened to the storage capacity of an artificial reservoir, which is dimensioned to balance societal costs and benefits in the light of an acceptable risk (i.e. the design return period). Similar to human reservoir design, ecosystems show evidence of optimizing the root zone, balancing guaranteed water access (at a certain return period) against carbon expenditures for root growth and maintenance (Kleidon and Heiman, 1998; Guswa, 2008; Schymanski et al., 2008; Gao et al., 2014a).

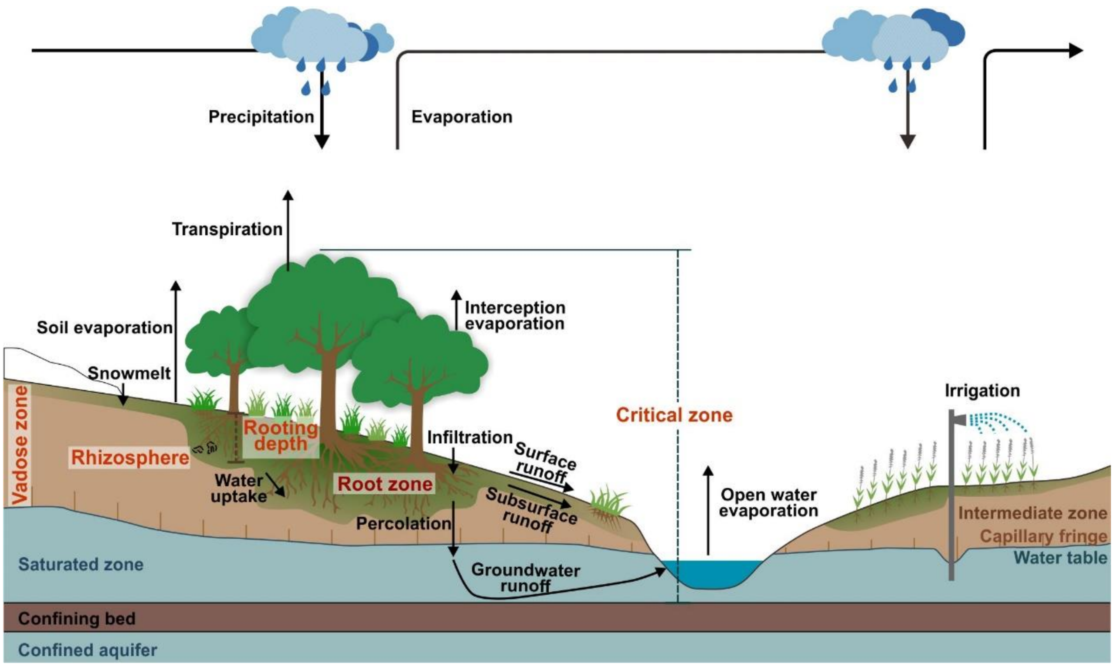

Figure 1. Schematic diagram of the root zone in terrestrial hydrological processes and atmospheric moisture cycling, showing the difference between root zone and other similar terms, such as vadose zone, rooting depth, rhizosphere and critical zone.

2.4 Root zone and “similar” concepts

2.4.1 Root zone *vs* vadose zone

The vadose zone (also known as the unsaturated zone) is the area underneath the land surface which forms the transition zone to the capillary fringe above the groundwater (Figure 1). The root zone is contained within the unsaturated zone, but is generally smaller. Below the root zone, the transition zone acts as a conduit facilitating percolation from the root zone to the groundwater with very limited phase changes of water (i.e. evaporation), and without directly affecting the water balance at the land surface. In other words, the water percolating into the transition zone from above will eventually recharge the groundwater (with some temporal delay depending on the depth of the groundwater and soil types) and finally contribute to river flow. Deep confined groundwater, which is minimally connected to surface processes, generally does not factor into surface runoff calculations (Fitts, 2002). Consequently, the root zone, functioning as the active layer that is located mostly within the vadose zone plays a pivotal role in catchment hydrology, determining in large part how catchments respond to precipitation events.

2.4.2 Root zone *vs* critical zone

The root zone, a key area where plants have evolved to adapt to their environment over time, constitutes the foundation of terrestrial ecosystems. As such, it is a vital *component* of the critical life zone on Earth (Banwart et al., 2017; Brantley et al., 2017). However, the definition of the critical zone remains a topic of debate. The most commonly accepted definition comes from the National Research Council in the U.S. (NRC, 2001): the critical zone is the near-surface layer of the Earth, encompassing vegetation, soil, water, and rocks, all of which are essential for sustaining life. According to this definition, the critical zone extends "from the canopy top to the base of the groundwater zone." (Figure 1). While there is widespread agreement on the upper boundary of the critical zone—the top of the vegetation canopy—the lower boundary is less defined and varies. For instance, some definitions cite the base of the groundwater zone (NRC, 2001), the bottom of the weathering zone (Guo and Lin, 2016), the base of active groundwater (Fan, 2016), or the storage of fresh groundwater (less than 50 years old) (Gleeson et al., 2016). Regardless of the specific version, the root zone is always included in critical zone definitions. Furthermore, the root zone is the most dynamic layer within the critical zone, connecting the canopy to groundwater and encompassing all components of the critical zone: water, vegetation, soil, air, and bedrock.

2.4.3 Root zone *vs* rhizosphere

The rhizosphere refers to the zone around roots where micro-organisms play crucial roles in biological processes essential for plant growth and health (Hiltner, 1904; Hartmann et al., 2008). It encompasses the roots themselves, the surrounding soil, and the narrow space between them, typically ranging from 1 to 4 millimeters (Kuzyakov and Razavi, 2019) (see Figure 1 and 4). There are similarities between the rhizosphere and the root zone. Both are dynamic and alive. However, the rhizosphere specifically refers to the soil volume immediately surrounding living roots, extending only a few millimeters from the root surface. It is primarily studied to understand direct interactions with micro-organisms and to assess nutrient depletion zones. In contrast, the root zone concept is applied in larger-scale hydrology, agronomy, and land surface studies to evaluate the total water and nutrient resources available to plants. This results in a significant difference in volume, spanning 2 to 3 orders of magnitude between the rhizosphere and the root zone. The rhizosphere is more aligned with biological and soil science on a micro-scale (Kuzyakov and Razavi, 2019), whereas the root zone is better suited for broader ecological and hydrological investigations within Earth systems.

3 Root zone in the Earth system

Earth system science is an interdisciplinary field to describe the Earth's structure and operations as a complex, integrated system (Steffen et al., 2020). Originating from early studies on interactions between the biosphere and geosphere, and influenced by concepts such as the Gaia hypothesis (Lovelock, 1979), Earth System science gained prominence in the 1980s in response to the need for a comprehensive 'science of the Earth'. In the latest conceptual model (Figure 3 in Steffen et al., 2020), the root zone assumes a central role as the interface between roots, soils, vegetation, lithosphere, hydrosphere, biosphere, cryosphere, atmosphere and human society's production and consumption (Figure 2). Despite its thin layer and containing only 0.13% of Earth's total freshwater (McCartney et al., 2022), the root zone profoundly influences land surface hydrology, land-atmospheric moisture exchange, and biogeochemical processes (Zehe et al., 2019).

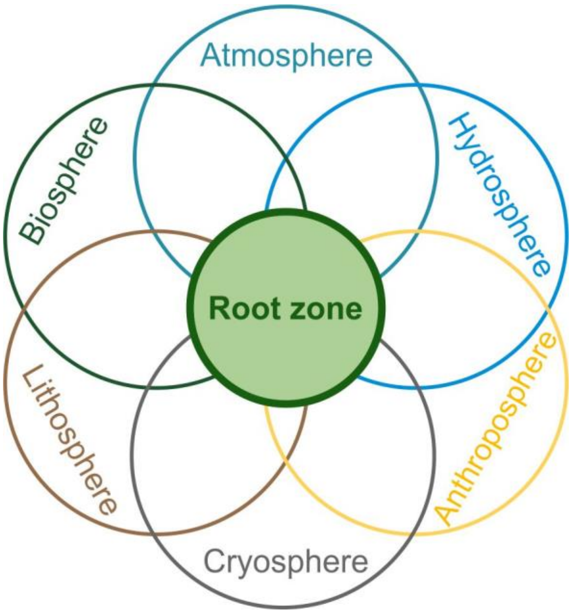

Figure 2. Root zone is the interface between hydrosphere, biosphere, lithosphere, atmosphere, cryosphere, and anthroposphere in the Earth system.

3.1 Roots and the Hydrosphere

The terrestrial water cycle begins with precipitation, which is initially intercepted by vegetation and ground cover. From there, it either returns to the atmosphere through interception evaporation, runs off to drainage systems as overland flows, or infiltrates into the soil, eventually percolating into the root zone. Once infiltrated, water can be stored for plant use through transpiration, percolate deeper to recharge groundwater, or flow laterally, through preferential pathways, to the stream. Transpiration rates are regulated by plant characteristics, atmospheric water demand, and the availability of moisture in the root zone.

Overall, these processes—evaporation, transpiration, runoff, groundwater recharge—are largely controlled by the moisture content in the root zone (Rodriguez-Iturbe and Porporato, 2004). Therefore, root zone moisture plays a critical role in determining how precipitation is partitioned among these different pathways and affects the overall storage dynamics of the root zone.

In the global water balance over extended periods, precipitation is partitioned between runoff and evaporation, with the root zone playing a crucial role in this distribution. According to ERA-5 reanalysis data, the average annual terrestrial precipitation is 745 mm/year, of which 295 mm/year (40% of precipitation) returns to the oceans as streamflow, while 440 mm/year (60% of precipitation) is evaporated back into the atmosphere by ecosystems (Gao et al., 2023a).

The largest terrestrial water flux to the atmosphere is through vegetation root water uptake, hence transpiration, which accounts for 60-90% of total terrestrial evaporation globally (Jasechko et al., 2013; Schlesinger and Jasechko, 2014; Coenders-Gerrits et al., 2014; Wang et al., 2014; Lian et al., 2018). Despite global average canopy interception having a storage capacity of only around 2 mm (compared to approximate 200 mm S_{Rmax}, see Gao et al., 2023a), interception plays a significant role in total forest evaporation due to its continuous activity in all rainfall events (Gerrits et al., 2010;

Sun et al., 2016).

In well-vegetated regions, soil evaporation is of minor relevance due to the protective effect of the canopy and litter layer, but also do due the lack of turbulent exchange with depth (Brutsaert, 2014). Conversely, in sparsely vegetated areas such as deserts, soil evaporation can be more substantial. Globally, soil evaporation contributes approximately 6% of total evaporation, with its significance being more prominent in arid than in humid regions (Wang-Erlandsson et al., 2014; Good et al., 2015; Zhang et al., 2017).

Plant roots, along with microbiotic and macrobiotic life, profoundly influence soil hydraulic properties and water-cycle dynamics by creating soil macropores and adding organic matter (Ponge, 2015). These macropores, formed through the presence of living or decaying roots but also by animal activity enhanced by the presence of vegetation, act as large cracks or voids that reinforce infiltration and facilitate rapid water drainage as preferential flow pathways. This capability reduces the duration of soil saturation, thereby mitigating conditions that could lead to root rot.

Furthermore, organic matter from decomposed roots contributes to cementation within soils, altering their internal structure. Soils rich in organic matter typically exhibit higher porosity and water holding capacity, crucial for retaining water in soil pores—a vital adaptation for terrestrial ecosystems in water-scarce environments.

The expansion of terrestrial ecosystems not only transforms hydrological processes within the root zone but also exerts significant impacts on the larger-scale water cycle (see Figure 1 and Sect. 4.4). Modeling studies indicate that terrestrial ecosystems enhance terrestrial precipitation by 40% (Xue et al., 2010). Comparisons between a green planet (fully forest-covered) and a desert planet (without vegetation) reveal that evaporation on continents triples and precipitation doubles in the former scenario (Fraedrich et al., 1999; Kleidon et al., 2000). These findings underscore the profound influence of root zone development in intensifying the global water cycle.

3.2 Roots and the Biosphere

Roots are indispensable organs enabling plants to thrive and reproduce across diverse habitats. They serve crucial functions such as absorbing water and nutrients, which are essential for plant growth and performance. Additionally, roots anchor and stabilize plants in the soil, store chemical energy produced via photosynthesis in leaves in the form of carbohydrates and thus as biomass (Shekhar et al., 2019), and play a pivotal role in sensing local resources like water, nutrients, and phosphate. This sensing ability allows plants to efficiently access resources that are often heterogeneously distributed in the substrate's complex network of pores and fissures.

The root zone represents the product of long-term co-evolution between the biosphere and its inorganic environment, shaped by climatic and geological factors within the Earth system (Huggett, 2023). Similar to the extensive global aboveground vegetation, the root zone likely spans a vast land area of approximately 103.9 million km^2 (70 % of total land area) (Ding et al., 2020).

Cutting-edge biological research has unveiled the root zone as a well-connected underground network of mycorrhizal fungi, akin to a nervous system, through which resources and information are exchanged among plants (Simard, 2018). This underscores that plants and their roots are integral components of a cohesive ecosystem rather than isolated entities. Further exploration of these interconnected relationships will be expanded upon in Section 4.1.5.

3.3 Roots and the Lithosphere

From a long-term evolutionary perspective, roots play pivotal roles in promoting rock weathering and soil formation. Roots possess the ability to sense and navigate through heterogeneous structures, circumventing obstacles at both microstructural (volumes less than mm^3) and macrostructural scales (Wang et al., 2020). They also act as "wedges," physically opening up substructures (Pawlik et al., 2016) to access water stored in the bedrock (McCormick et al., 2021), while root-associated fungi further contribute to rock weathering and the enlargement of fractures (Schenk, 2008).

In the short term, roots exert a stabilizing effect by anchoring soil, which reduces erosion rates, enhances slope stability, and mitigates risks of landslides and debris flows (Vannoppen et al., 2017). Forest communities are particularly effective in minimizing erosional processes and supporting stability along hillslopes and riverbanks (Pawlik et al., 2016). Furthermore, roots significantly enhance soil strength, lowering the likelihood of shallow landslides (Cohen and Schwarz, 2017). The reduction in sediment flow facilitated by roots also yields basin-scale impacts on downstream river geomorphology (Ielpi et al., 2022; Cao et al., 2023).

3.4 Roots and the Atmosphere

The root zone plays a pivotal role in land surface and climate modeling, a fact widely acknowledged in scientific literature (Milly and Dunne, 1994). The moisture status within the root zone critically influences water, energy and carbon exchange fluxes between the land surface and the atmosphere, primarily through root water uptake and transpiration, as well as the associated latent heat flux, which enhance atmospheric water vapor. Transpiration, as a component of total land evaporation, depends on the balance between atmospheric water demand and the moisture supply in the subsurface and accessible to plant roots. Vegetation and land cover thus actively regulate the exchange of water, energy, and carbon between the root zone and the atmosphere.

The root zone is not only influenced by but also actively influences the Earth's climate and the large-scale water cycle (Jackson et al., 1996). Firstly, evaporation entails a combined water and energy flux. From that perspective, incorporating accurate root zone data has significantly improved simulations of the land surface energy budget, particularly the latent heat flux (Zeng et al., 1998; Zheng and Wang, 2007). Secondly, compared to soil evaporation and canopy interception, the root zone of vegetation can access the deeper subsurface to extract water for transpiration. By supplying vapor to the atmosphere, the root zone is therefore a major component to sustain atmospheric moisture levels and the associated downwind precipitation, which shapes the long-term climate pattern over considerable distances (van der Ent et al., 2010; van der Ent and Savenije, 2011; Wang-Erlandsson et al., 2018). Approximately 56% of transpiration to return to land as precipitation (Figure 1, and Van der Ent et al., 2014). Root-zone helps transpiration to be sustained during dry periods, and plays a particularly important role for dry season length and buffers against variability in precipitation (e.g., Keys et al., 2016, O'Connor et al., 2021).

3.5 Roots and the Cryosphere

The connection between the root zone and the cryosphere is particularly pronounced in regions where vegetation covers frozen ground. In permafrost areas, the active layer undergoes seasonal freeze-thaw cycles, defining the maximum depth of thawing. Roots are constrained to grow within this active layer—the uppermost soil layer that thaws annually—because the permanent frozen layer below it and the ice layer are impermeable to root penetration (Blume-Werry et al., 2019).

In cold climates, the effects of snowmelt on the inflow to the root zone and soil freeze-thaw processes are crucial considerations (Gao et al., 2020, 2022; Wang-Erlandsson et al., 2016; Zhao et al., 2016; Dralle et al., 2021). Climate change exacerbates these dynamics by causing permafrost thawing, which expands the active layer and lowers the groundwater table. This thawing process opens up previously inaccessible soil volumes for potential root growth. The expansion of the active layer and changes in the groundwater table profoundly impact rooting depth and distribution in permafrost regions.

The dynamics of the active layer and variations in root zone storage are intricately intertwined in permafrost regions, influencing soil evaporation, plant transpiration, hydrologic connectivity, and runoff generation (Sugimoto et al., 2002; Suzuki et al., 2021). Understanding these interactions is essential for predicting how climate change will affect terrestrial ecosystems and hydrological processes in cold regions.

4 Heterogeneities within root zone

4.1 Reductionist perspective: processes within the root zone

From a reductionist perspective, enormous heterogeneity and complexity of root zone features are characterized and catalogued by hydrologists, ecologists, pedologists and microbiologists (McDonnell et al., 2007; Lin, 2010; Gao et al., 2018; Kuzyakov and Razavi, 2019). In this section, we outline the complexities within the root zone across five key categories: soil heterogeneities, rooting distribution heterogeneity, flux heterogeneities, plants' belowground zone of influence, rhizosphere and mycorrhizal fungi.

4.1.1 Soil heterogeneity

Soil heterogeneity exhibits variability in both horizontal and vertical dimensions, characterized by distinct horizons with diverse properties such as texture (varying proportions of sand, clay, and slit), mineral composition, and organic content. Soil also possesses varied hydraulic characteristics including porosity, moisture retention capacity, wilting point, and plant-available moisture. It consists of a complex mixture of minerals, organic matter, living organisms, gases, and water, earning it recognition as "the most complicated biomaterials on the planet" (NRC, 2009; Lin, 2010).

Despite its strong connection to soil, the root zone does not necessarily align with soil depth (Figure 3) (Hahm et al., 2024). In many cases, particularly in regions with deep soils, the root zone is confined to the uppermost active layer of topsoil where the majority of hydrological and biogeochemical processes occur, even though the soil may extend much deeper. In water-stressed environments (Evaristo and McDonnell, 2017; Wang et al., 2022) or in regions with shallow groundwater (Fan et al., 2017) roots can reach the groundwater, expanding the definition of the root zone to include parts of the groundwater (see Singh et al., 2020). The depth to bedrock serves as the lower boundary of the soil, defining its overall depth. However, in karst and other regions with shallow soil, roots can penetrate bedrock fissures to access water despite the challenging substrate conditions (McCormick et al., 2021; Lapides et al., 2023).

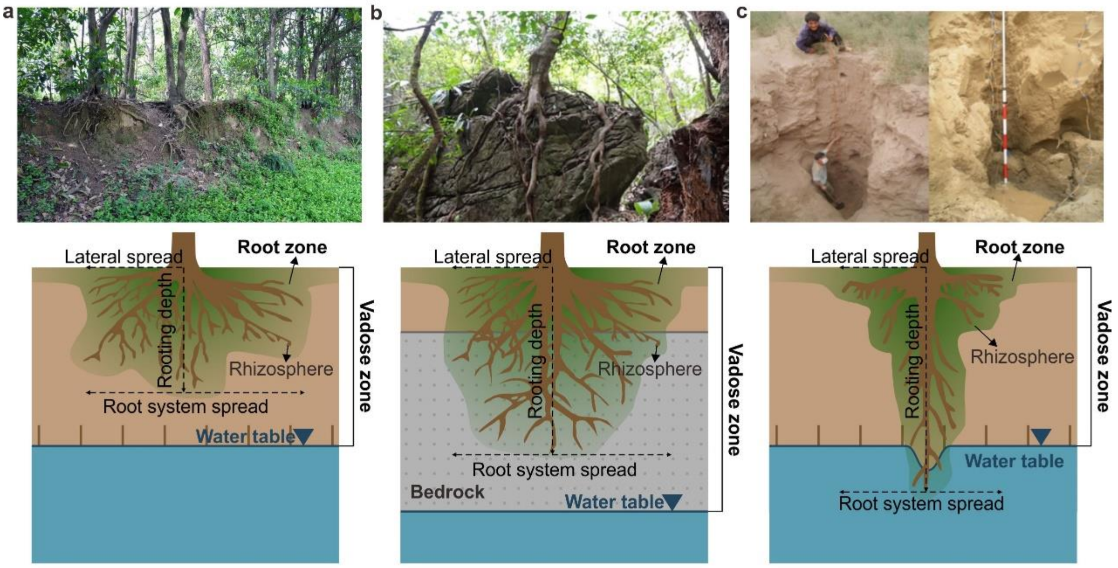

Figure 3. Root zone is different from soil depth. (**a**) is the root zone in moderate climate. Root zone is the upper area of soil; (**b**) root zone contains not only soil but also bedrock; (**c**) root zone contains unsaturated zone and groundwater, for example the phreatophytic roots in arid regions (Wang et al., 2018).

4.1.2 Rooting distribution heterogeneity

Root distribution pattern in the soil profile plays a crucial role in determining how effectively plants can access water and nutrients. These patterns encompass the vertical and lateral spread of both coarse and fine roots, as well as the overall root density across the three-dimensional soil profile. Rooting depth, a key trait widely utilized in Earth system modeling, specifically refers to the depth to which roots extend vertically. However, it is important to note that root distribution does not always directly correlate with rooting depth (Zheng and Wang, 2007). For instance, an ecosystem dominated by deep-rooted plants with low root density may have a smaller overall root zone, and thus a smaller accessible water volume, compared to one with shallow-rooted plants that have higher root density (Singh et al., 2020; van Oorschot et al., 2021).

Despite the critical importance of root distribution and concerted ongoing research efforts that compile an impressive richness of observations (e.g. Schenk and Jackson, 2005; Tumber-Davila et al., 2022), upscaling root distributions remains challenging. This is due to the fact that although observations are available for several thousand of individual plants globally, these are essentially point/plot-scale observations for which spatial covariance fields remain largely unknown. It is worth emphasizing that even with detailed data on root distribution for individual plants, determining the precise extent of the root zone is challenging due to the complex network of pores, fissures in soils and bedrock, intricate hydrodynamic gradients, and mycorrhizal fungi network (e.g. Casper et al., 2003; see Figure 4).

4.1.3 Flux heterogeneity: preferential flow

Traditionally in hydrology, the infiltration process was believed to be primarily controlled by matrix flow, assuming soil texture dictates hydraulic properties and infiltration capacity (Beven, 2021). However, mounting evidence now indicates that preferential flow routes rapidly transmit free water through the subsurface, dominating water movement across various scales (Uhlenbrook, 2006; Liu et al., 2012; Beven and Germann, 2013). In water-limited environments, the rooting systems of plants strongly influence infiltration capacity, velocity, and depth (Schenk & Jackson, 2002; Schenk, 2008). Infiltration replenishes moisture in the root zone through preferential pathways, while excess water either runs off or percolates into groundwater.

Recent research highlights the crucial role of mucilage exuded from roots and rhizosphere bacteria in forming liquid bridges at the root–soil interface. These bridges significantly impact the mechanical stability and hydraulic properties within the root zone (Bengough, 2012). The complexity introduced by preferential flow channels and their influence on hydraulic properties challenges the traditional soil-centric Darcy-Richards framework (Beven, 2012; Gao et al., 2023b).

4.1.4 Plant’s belowground zone of influence

The concept of a plant's belowground zone of influence refers to how roots absorb water and nutrients not from a fixed area, but from a highly dynamic and irregular zone (Casper et al., 2003). This zone exhibits complex and variable hydraulic and nutrient gradients between roots and their surroundings. From a reductionist, root-centered micro-scale perspective, the belowground zone of influence quantifies how the influence of roots decreases with distance from the stem. The hydrological processes and shape of root zones are extremely variable, plastic, irregular, and dynamic, making it effectively impossible to quantify or model this zone accurately.

However, viewing the root zone as a holistic system reveals emergent behaviors and spatial patterns that enable us to move beyond the complexities of gradient-based models and the heterogeneity of the plant's belowground zone of influence (see Figure 4).

4.1.5 Rhizosphere and mycorrhizal fungi

The rhizosphere, as the dynamic area at the plant root-soil interface, is characterized by a multitude of biogeochemical processes driven by physical activities, such as water and nutrient dynamics (Figure 4a, and Bengough, 2012; Daly et al., 2017). The rhizosphere supports microbial growth (e.g., populations of bacteria ranging from 10^7 to 10^{12} per gram of rhizosphere soil), thereby stimulating biochemical processes crucial for plant nutrition and health (Hinsinger et al., 2009). Moreover, the mucilages and exudates of plants’ roots, forming as soil aggregates, significantly alter rhizosphere’s hydraulic properties, such as infiltration capacity, water holding capacity, and preferential flow (Daly et al., 2017).

Mycorrhizal fungi form a complex network of roots and fungal hyphae, often referred to as the 'wood wide web' (Beiler et al., 2009). These fungi create an underground continuous network that connects an estimated 90% of land plant species (Bonfante and Genre, 2010), facilitating the exchange of resources such as carbon, water, and nutrients, as well as information about environmental conditions and threats such as insect infestations (Bonfante and Genre, 2010).

The existence of mycorrhizal fungi dramatically increases the root zone water and nutrient absorption capacity. The absorption fine roots are usually ticker than 0.2 mm (Strand et al., 2008; Taylor et al., 2013), which means roots can only grow in macropores. Thus roots have limited absorption capacity, can only use 4-7% of available soil volume (Guo et al., 2008). But one spoon of soil can have mycorrhizal fungi as long as 1 km, and as thin as 2-10 microns (Allen, 2007), which allows mycorrhizal fungi growing in micropores among fine minerals, which are unreachable for roots. These fungi enhance plant water uptake, to be 7 times higher than without mycorrhizal fungi

(Zhang et al., 2018), particularly beneficial during periods of water stress (Augé, 2001; Püschel et al., 2020), by promoting water availability and transportation.

The intricate network of mycorrhizal fungi functions akin to neural tissue in animals, allowing the root zone to respond to environmental changes—such as climate variations, water availability, nutrient levels, and threats—in a holistic and predictable manner.

4.2 Reductionists' root zone models

Although the hydrology community has advocated moving beyond heterogeneities for some time (McDonnell et al., 2007), reductionist modeling remains prevalent in describing the root zone across hydrological models, dynamic vegetation models (DGVMs), and land surface schemes in Earth system models. Rooting depth varies among plant functional types (PFTs) and is in these models typically treated as a fixed parameter using lookup tables. Soil water holding capacity, determined in laboratories, defines the amount of water retained under gravitational free drainage (van Oorschot et al., 2021). Soil depth, ranging widely from 1 meter to over 10 meters or until bedrock, is a critical parameter (Hidy et al., 2021; Wiltshire et al., 2021). Soil profiles are segmented into layers, varying from 3 to more than 10 (Seneviratne et al., 2010). The maximum storage capacity of the root zone, S_{Rmax}, combines rooting depth and soil water holding capacity derived from soil texture data. In advanced models such LPJ-GUESS, root distribution follows an exponential function constrained by maximum rooting depth, groundwater levels, and nutrient distribution (Smith et al., 2014). Furthermore, DGVMs integrate dynamic root modules to simulate root growth, architecture, and distribution in response to soil water and nitrogen availability (e.g., Lu et al., 2019).

However, we argue that this traditional perspective of the root zone, which assumes the whole is the sum of its parts (see Table 1 and Figure 4a), is subject to several issues. First, the intricate network of pores and fissures in the substrate, extending both laterally and in depth, with complex gradients of water and nutrients, cannot be accurately simulated by mechanically combining rooting depth and soil properties (Figure 4a). Second, this approach lacks detailed observations of root density, vertical and lateral distribution, leading to significant uncertainties related to either the use of strong assumptions that may not by supported by data or heavy reliance on parameter calibration. Third, the method overlooks fractal patterns in soil structure, pore networks, root morphology, and preferential flow paths. These fractal patterns embody organized complexity or simplicity that could enhance the realism of models, but they are typically broken up in reductionist approaches. Fourth, the root zone exhibits gradients in chemical, biological, and physical properties that vary radially and longitudinally along roots (McNear, 2013; Kuzyakov and Razavi, 2019). For instance, hydraulic redistribution is crucial for trees, redistributing water vertically from deeper, wetter soil layers to shallower, drier layers during nighttime (Figure 4a) (Bleby et al., 2010; Nadezhdina et al., 2010), but also laterally between individual plants (Hafner et al., 2021). Fifth, recent studies of the rhizosphere highlight the extraordinary complexity of underground root systems (e.g. Daly et al., 2017), which are difficult to adequately describe by reductionist methods. However, there is evidence that from these small-scale heterogeneities relatively stable and simple pattern emerge on larger scales. For example, small-scale studies of mycorrhizal fungi demonstrate that the root zone system responds as a whole to changes, providing a microscale foundation for holistic approaches to root zone modeling (Figure 4).

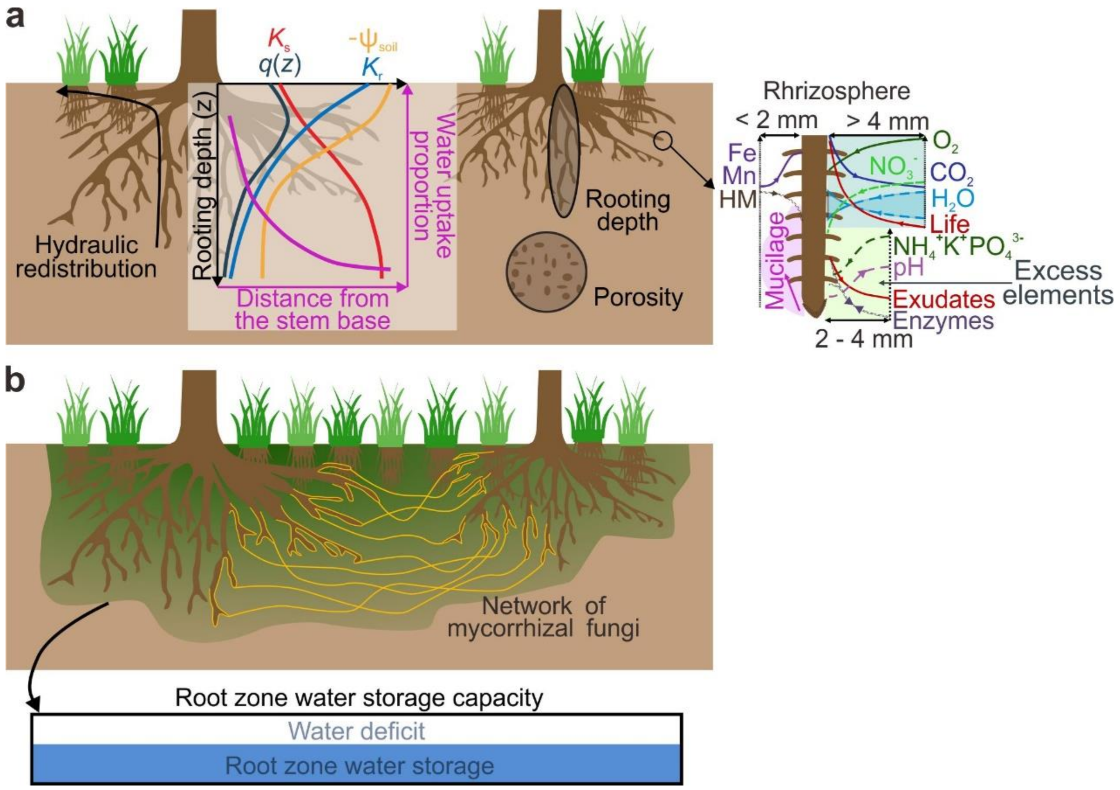

Figure 4. Comparison of reductionist (**a**) and holistic (**b**) views of root zone and root zone water storage capacity. (**a**) The reductionist perspective estimates root zone storage capacity and transpiration based on rooting depth and soil properties, assuming a static view primarily relying on soil information. Root water uptake as a function of depth ($q(z)$) is shown for a soil profile with a dry upper layer (leading to more negative soil water potential (ψ_{soil}) and low soil hydraulic conductivity (K_s)) and a deeper soil layer with higher water content (leading to less negative ψ_{soil} and higher K_s). At the whole-plant scale, root conductivity (K_r) is correlated with the root surface area, which decreases exponentially with depth. Proportion of plants that took up water as a function of distance from the stem based is shown on the right side of graph, which decreases with distance (adapted from Casper et al., 2003; Tumber-Dávila et al., 2022; Bachofen et al., 2024). Top right figure shows the 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) (**b**) The holistic perspective views root zone storage as a volume per unit area, emphasizing an average depth. It estimates root zone capacity and transpiration based on plant water demand, reflecting a dynamic view influenced by climate and plant adaptation. The mycorrhizal fungi network enables the root zone to respond to environmental changes as a unified system.

5 Emergent behavior of root zone as a holistic system

5.1 Holistic perspective in hydrology

Holistic perspectives regard the root zone as an integrated living system shaped by fractal patterns, influenced by long-term self-organization and co-evolution. In contrast, reductionist models focus on determining "How deep is the root zone?". Holistic approaches instead ask broader questions such as "What is the size of the root zone?" and "How much moisture can it buffer?". Viewing the root zone holistically allows for more predictable behavior, enabling simulation with simpler models, based on widely and readily available data.

5.1.1 Holistic root zone approach

The root zone, located beneath the surface and not directly observable, can be characterized using an inverse modeling approach to infer its systematic behavior. Various parameterizations driven by land surface water and energy fluxes, such as precipitation, evaporation, radiation, and biomass observations like net or gross primary production (Kleidon, 2004), play crucial roles in this process.

The mass curve technique (MCT), elsewhere also referred to as Memory Method (van Oorschot et al., 2021, 2024) serves as an inverse model that employs a water-deficit approach based on observed land surface water budgets to estimate root zone processes (see Figure 5) (Gao et al., 2014a; Wang-Erlandsson et al., 2016; Kühn et al., 2022). This holistic method allows hydrologists and ecologists to derive S_{Rmax} from ecosystem-scale observations of liquid water inflow (F_{in}), i.e. the sum of precipitation (de Boer-Euser et al., 2016), snowmelt (Dralle et al., 2021), and irrigation (van Oorschot et al., 2024) and water outflow (F_{out}, evaporation). Time series data of inflow and outflow are utilized to infer cumulative water deficits during dry periods (Equations 3 and 4). The largest cumulative deficit observed over a specific return period can be considered as representing the actual S_{Rmax} (Equation 5).

$$A_{t_n \rightarrow t_{n+1}} = \int_{t_n}^{t_{n+1}} F_{out} - F_{in} dt \tag{3}$$

$$D_{t_{n+1}} = max(0, D_{t_n} + A_{t_n \rightarrow t_{n+1}}) \tag{4}$$

$$S_{\mathrm{Rmax}} = \max(D_{t_1}, D_{t_2}, \dots, D_{t_{end}}) \tag{5}$$

$A_{t_n \rightarrow t_{n+1}}$ is the water deficit in $t_{\mathrm{n+1}}$ day, $D_{t_{n+1}}$ is the accumulative water deficit in day $t_{\mathrm{n+1}}$.

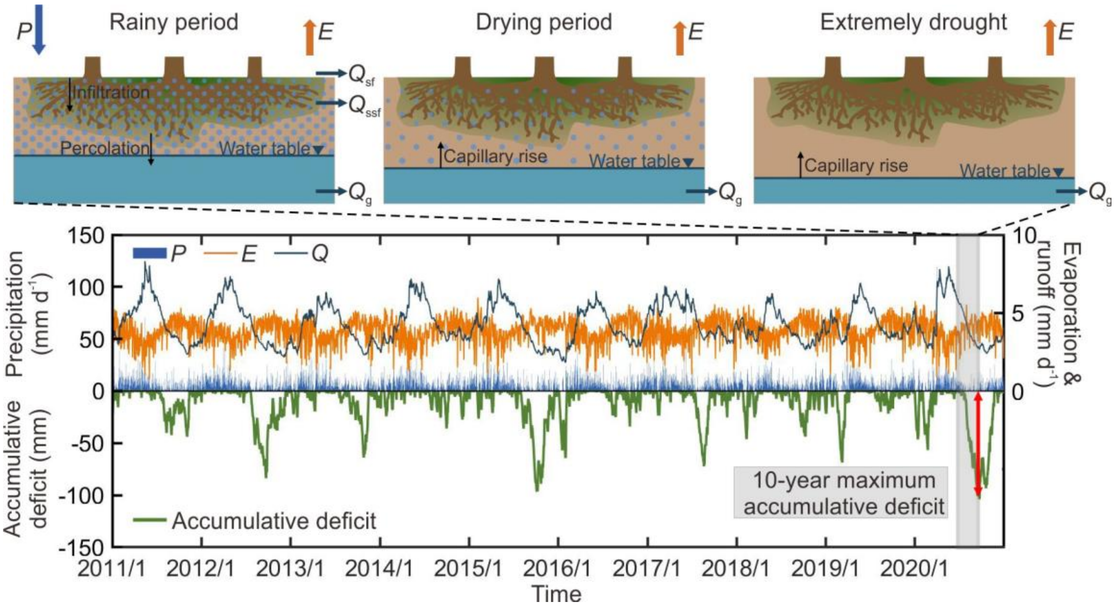

Figure 5. The dynamic change of water deficit in root zone from the wet season to dry season. On

the upper panel, the conceptual illustration of the water deficit change in root zone is shown with its effect on hydrology. P and E represent precipitation and evaporation respectively. Q_{sf}, Q_{ssf} and Q_{g} represent surface, subsurface and groundwater runoff respectively. The lower panel shows the precipitation (P), evaporation (E), runoff (Q) and accumulative water deficit in root zone from 2011 to 2020. Note that the real world root zone storage capacity cannot be smaller than the value S_{Rmax} estimated with the above method, as otherwise there would not have been sufficient water available and accessible for vegetation to sustain the observed evaporation (F_{out}). S_{Rmax} is therefore in any case a minimum and thus a lower limit to the root zone storage capacity. In principle, it can be argued that S_{Rmax} could be larger than that. However, increasing evidence from studies that estimate S_{Rmax} with optimality approaches (e.g. Kleidon, 2004; Guswa, 2008; Schymanksi et al., 2008) or as model calibration parameter (e.g. Gao et al., 2014; Njzink et al., 2016; Hrachowitz et al., 2021; Wang et al., 2024) suggests that it is not likely that the real world root zone storage capacity is larger than the S_{Rmax} associated with an ecosystem-specific dry spell return period. Instead, the results of these studies suggest that vegetation optimizes its below- and above-surface resource allocation to allow sufficiently large root systems to access water (and nutrients) in dry periods while also allowing sufficient above-surface growth to allow survival in the competition for light and for increased strength against windfall. In other words, the root system and thus S_{Rmax} is as large as necessary but not larger than that.

The holistic perspective requires integrated measurements (Reichstein et al., 2014), incorporating methods such as lysimeters and eddy covariance for determining land surface fluxes, satellite remote sensing, and catchment-scale water balance assessments (Gao et al., 2014a; Wang-Erlandsson et al., 2016; Kühn et al., 2022; Stocker et al., 2023). Lysimeters are particularly valuable tools for quantifying the water balance in the root zone, offering unique insights, especially in comparisons between vegetated and non-vegetated systems, highlighting the influence of vegetation dynamics on the water cycle (Seneviratne et al., 2012; Scanlon et al., 2005).

Satellite remote sensing provides extensive spatial and temporal data on land surface water fluxes, including precipitation and evaporation, crucial for deriving root zone processes. Catchment-scale water balance studies encompass variables such as precipitation and streamflow, offering valuable insights into long-term average evaporation patterns. Additionally, S_{Rmax} serves as a key parameter in conceptual hydrological models, often calibrated based on catchment precipitation and streamflow data (Gao et al., 2014b; Liang et al., 2024; Wang et al., 2024).

5.1.2 Climate and topography controls S_{Rmax}

The holistic perspective in modeling frameworks can be traced back to the bucket model used in the first global climate model by Manabe in 1969. In this early study, S_{Rmax} was globally set at 150mm, providing a reasonable estimation of the global average (Wang-Erlandsson et al., 2016; Gao et al., 2023a; Stocker et al., 2023). However, S_{Rmax} varies significantly across different climate zones and ecosystems.

In tropical rainforests (see Figure 6), where rainfall is abundant throughout the year, S_{Rmax} tends to be small because water availability is not a limiting factor, allowing forests to develop tall canopies to compete for light. In temperate climates, where rainfall starts to constrain growth, ecosystems typically allocate more resources underground, enhancing their root zone capacity. In savannas, characterized by strong precipitation seasonality, ecosystems further expand their root zones to cope with prolonged droughts, often at the expense of aboveground biomass. Grasslands, on the other hand, may enter dormancy during droughts, exhibiting very limited S_{Rmax} (Figure 6).

Interestingly, research has shown that ecosystems optimally adjust their root systems to their specific environments (Schymanski et al., 2008; Guswa, 2010), adapting to drought periods that vary from 5 to 40-year return periods depending on the ecosystem type (evergreen, deciduous, grassland, etc.) (Gao et al., 2014a; Wang-Erlandsson et al., 2016).

At the landscape scale, the spatial distribution of S_{Rmax} is largely influenced by topography (Fan et al., 2017; Gao et al., 2019). Topography also plays a critical role in determining runoff generation mechanisms, such as saturated overland flow in wetlands, subsurface storm flow in hillslopes, and infiltration excess overland flow on terraces (Savenije et al., 2010; Gharari et al., 2014).

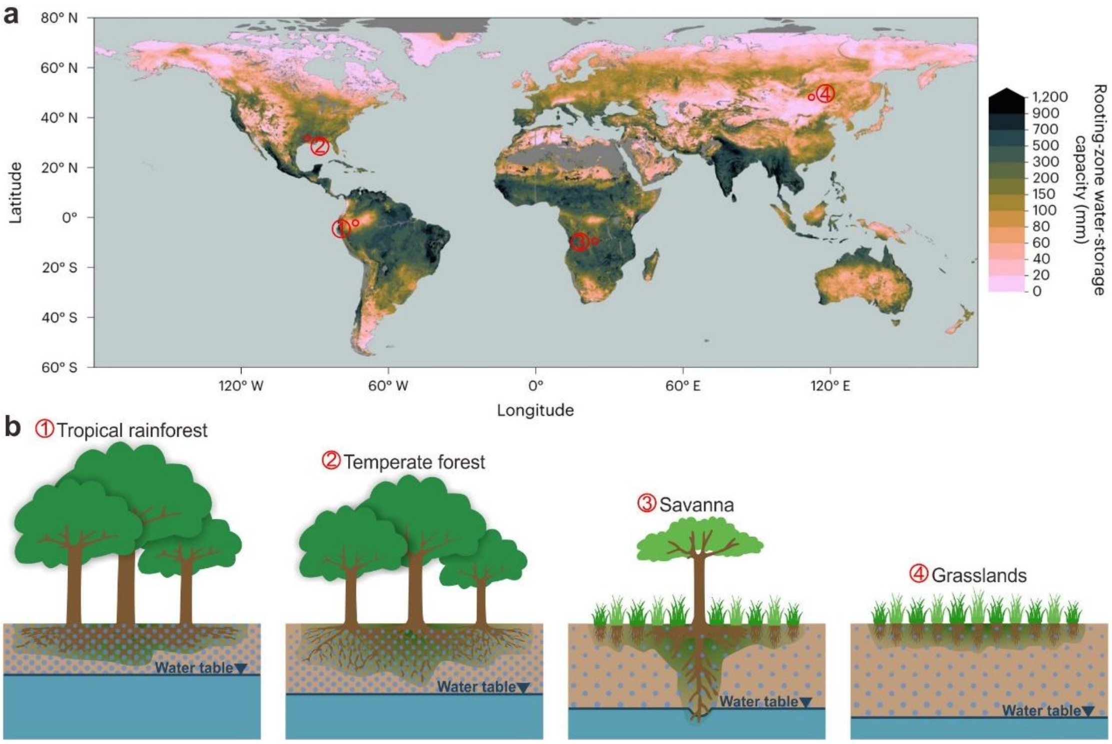

Figure 6. (**a**) The global root zone storage capacity (from Stocker et al., 2023). (**b**) The conceptual illustration of aboveground biomass and root zone in different climate zones.

5.1.3 Holistic root zone impacts on groundwater

The influence of the root zone on catchment hydrology is prominently observed through its impact on groundwater dynamics and baseflow recession. The root zone plays a crucial role in controlling water percolation to groundwater (Collenteur et al., 2021). Groundwater recharge and streamflow generation are closely linked, as runoff is typically derived from groundwater under most conditions (Ali et al., 2011). Additionally, the root zone influences evaporation and plant transpiration from groundwater sources. Surface soil and root zone drying are moderated by upward capillary flow from the subsurface, sustaining evaporation during dry periods while reducing groundwater recharge over longer timescales.

A well-documented phenomenon is the diurnal cycle of streamflow and groundwater table fluctuations, particularly notable in arid and semi-arid catchments (Lundquist and Cayan, 2002; Wang et al., 2014; Yue et al., 2016). Vegetation, particularly in riparian areas, directly accesses groundwater for transpiration. Daytime root water uptake leads to declines in water tables, whereas water tables recover at night when transpiration rates diminish (Yue et al., 2016). This illustrates the direct hydraulic connection between root water uptake, groundwater dynamics, and river streamflow.

5.2 Holistic root zone in hydrology modeling

The concept of thresholds and hydrologic connectivity associated with runoff processes is crucial for understanding hydrological responses at both hillslope and catchment scales (Saffarpour et al., 2016), with the root zone playing a pivotal role as an integrated system. It is widely observed that runoff generation does not occur until the root zone reaches a critical moisture threshold, known as field capacity (Tromp-van Meerveld and McDonnell, 2006). Once this threshold is surpassed, the outflow pathways are activated, leading to runoff generation. This mechanism is often referred to as fill-and-spill (McDonnell et al., 2021) or store-and-pour (Phillips, 2022).

At the landscape scale, topography emerges as a primary factor influencing the mechanisms of runoff generation. Due to landscape heterogeneity (including topography and vegetation cover), the S_{Rmax} exhibits spatial variability. In many cases, S_{Rmax} increases with the elevation above the nearest drainage (HAND) (Fan et al., 2017). Consequently, saturation and runoff generation do not occur uniformly across an entire catchment (Hewlett and Hibbert, 1967; Arnbroise et al., 2004; Beven, 2012; Gao et al., 2019). Typically, during the onset of wetting seasons, riparian zones near the drainage experience the critical threshold first, initiating saturation excess flow. As precipitation and root zone moisture increase, the contributing areas expand, a phenomenon known as the variable contribution area theory (Arnbroise et al., 2004). Accounting for this spatial heterogeneity of the root zone significantly improves the performance of runoff simulations (Gao et al., 2019).

These conceptual models are widely applied in global hydrological prediction practices, albeit with varied parameterizations and terminologies (e.g. Zhao, 1992; Perrin et al., 2003; Clark et al., 2008; Beven, 2012; Fenicia et al., 2014; Gao et al., 2019). In land surface and global hydrology studies comparing reductionist and holistic approaches, it is noteworthy that despite its simplicity, the holistic method often outperforms more complex reductionist approaches in runoff simulation (Mao and Liu, 2019; Wang et al., 2021), particularly in ungauged basins (Hrachowitz et al., 2013). Recent studies highlight the potential of using climate-controlled root zone parameters to enhance water flux simulations in land surface models such as HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land), resulting in improved discharge simulation correlations across different regions (van Oorschot et al., 2021).

Moreover, the holistic approach to the root zone is gaining traction in studies of water quality, solute transport, and transit times, presenting a promising new framework for integrating material transport through the entire system (Harman and Fei, 2024).

6 Root zone in the Anthropocene

6.1 The impacts of climate change

Climate exerts significant control over root zone dynamics. The root zone plays a critical role in determining ecosystem resilience to droughts and climate variability, alongside other factors such as shifts in species composition and physiological adjustments like leaf shape and stomatal regulation (Zhang et al., 2023). Root growth is highly dynamic and responsive to environmental changes, with rapid carbon transfer from leaves to roots and soil organisms occurring within hours to days across different ecosystems (Melkikh and Sutormina, 2022).

The spatial variability of S_{Rmax}, reflecting climatic conditions, has been well documented (Kleidon and Heimann, 1998; Gao et al., 2014a; Wang-Erlandsson et al., 2016; Stocker et al., 2023), suggesting that temporal variations in S_{Rmax} are also plausible under changing climate regimes. Local factors such as topography and groundwater dynamics further influence root zone dynamics, with observations indicating rapid root growth towards declining water tables in desert phreatophyte vegetation (Orellana et al., 2012; Wang et al., 2018; Kuzyakov and Razavi, 2019).

At the basin scale, temporal evolution of S_{Rmax} in response to climatic variability across multiple decades, has been reported by several studies (Bouaziz et al., 2022; Tempel et al., 2024; Wang et al., 2024). Globally, analyses based on ERA-5 reanalysis data indicate an 11% increase in global average S_{Rmax} over the past four decades (1982-2020), driven by intensifying drought conditions (Xi et al., 2024). This widespread increase in S_{Rmax} has been validated through dynamic identifiability analysis (DYNIA) algorithms using observed hydrometeorological data from U.S. catchments (Liang et al., 2024).

6.2 The impacts of land-use and land management activities

6.2.1 Agriculture

Agricultural activities exert significant influence on the root zone, impacting various aspects crucial for food production and food security (Eisenhauer et al., 2024). Practices such as irrigation, fertilization, tilling, non-point source pollution, and salinization predominantly occur within the root zone, shaping its characteristics and functionality.

Ploughing, a fundamental agricultural practice, plays a pivotal role in altering and determining root zone depth. Over time, intensive cultivation can lead to the formation of a plough pan, typically situated 15 to 30 cm below the soil surface in clay-rich soils. This compacted layer acts as a barrier beneath the root zone, limiting water percolation and restricting root growth to the relatively shallow soil layer above it (Li et al., 2019). In such scenarios, the moisture holding capacity of the topsoil becomes critical in defining the root zone storage capacity.

In irrigation agriculture, where additional water is supplied to the root zone during dry periods, the S_{Rmax} often becomes smaller compared to natural conditions with similar climates (Xi et al., 2021; Hauser et al., 2022; van Oorschot et al., 2024). Studies indicate that due to irrigation practices (excluding considerations of climate change impacts), rooting depth can be reduced by approximately 5%, equivalent to an approximate loss of 8 cm in depth or about 11,600 km^3 of rooted volume (Hauser et al., 2022). At a global scale, research has shown a consistent decrease in S_{Rmax} in croplands when irrigation practices are factored in as an additional water supply (van Oorschot et al., 2024).

6.2.2 Deforestation / Afforestation

Deforestation can significantly reduce S_{Rmax} (Hrachowitz et al., 2021). Recovery of S_{Rmax} following deforestation can take more than a decade to restore to previous levels (Nijzink et al., 2016). Conversely, regions experiencing woody encroachment often see root depths deepening by approximately 38 cm compared to the previous dominant vegetation (Hauser et al., 2022).

The root zone's role extends to evaluating the outcomes of large-scale ecological initiatives. For example, projects like China's "grain-to-grass" and "three norths afforestation projects" have proven beneficial for soil conservation, flood control, biodiversity enhancement, and carbon sequestration (Chen et al., 2019; Li et al., 2021). However, these initiatives have also increased water consumption through evaporation, posing challenges for water management in arid regions where societal water demands compete with ecosystem services (Feng et al., 2016). The underground root zone is the key piece in the puzzle, to connecting the isolated dots, and explaining all these ecological and hydrological phenomena in one framework.

Transitioning from traditional blue water management to integrated water resources management involves incorporating both blue- and green-water considerations—surface and groundwater—into a unified framework (Falkenmark, 2000). Root zone moisture plays a pivotal role in linking land surface fluxes, water resources, soil erosion, and carbon sequestration, thereby influencing the success and sustainability of such ambitious ecological projects (Sun et al., 2020).

6.2.3 Urbanization

Urbanization has profound effects on the root zone, transforming it from a permeable to an impermeable structure, which leads to increased stormwater runoff and reduced vegetation evaporation, as noted by Hao et al. (2018). Furthermore, urbanization significantly impacts the underground mycorrhizal fungi network, altering the hydrological processes within the root zone and catchment areas, as well as influencing the land surface energy budget. These changes contribute to intensified urban inundation and exacerbate the urban heat island effect (Fletcher et al., 2013).

There is growing interest in leveraging vegetation to manage hydrology in urban environments, exemplified by initiatives like China's "Sponge City" initiative (Xia et al., 2017). The root zone acts as a natural sponge in larger natural landscapes such as forests and grasslands, while green roofs and urban gardens serve as smaller-scale sponges within cities and neighborhoods. Increasing the S_{Rmax} has the potential to enhance flood prevention, improve water purification, mitigate the urban heat island effect, and enhance the aesthetic value of urban areas (Palmer et al., 2015).

7 Outlook

7.1 Observations

Accurately measuring root traits and characteristics of the root zone is among the most challenging tasks in ecological, agricultural, and hydrological research, particularly in field studies. For instance, determining the rooting depth of grasses and crops typically involves soil core sampling, while estimating coarse tree roots relies on allometric equations, and fine tree roots are assessed using soil cores. Despite efforts such as the global rooting depth synthesis study covering 2200 observations worldwide (Fan et al., 2017) and others (Tumber-Davila et al., 2022), this remains a relatively small sample compared to the vast number of 3.04 trillion trees globally (Crowther et al., 2015), not to mention the numerous grasses and agricultural crops. Consequently, descriptions of spatial distribution of root systems remain uncertain at scales from hillslope to global.

Remote sensing products such as SMAP and SMOS provide relatively high-resolution estimates of near-surface moisture, but their capabilities are confined to the top few centimeters of soil (Xu et al., 2021). Estimating root zone moisture from surface measurements involves specific assumptions and different types of models (Entekhabi et al., 2010; Reichle et al., 2019; Bouaziz et al., 2020; Kim et al., 2023). In Earth System Models (ESMs), uncertainties in projections of dry-season water availability are considerable, sometimes exceeding 200% of the ensemble mean, underscoring the need for more accurate observational data (Dong et al., 2024, under review).

To deepen our quantitative descriptions of root zone hydrology, in particular from a holistic perspective, additional experiments and measurements across diverse climates and landscapes are crucial. Methods such as field control experiments, rhizobox studies (Nie et al., 2013; Zhou et al., 2022; Maan et al., 2023), and long-term lysimeter measurements (Scanlon et al., 2005) are essential. Interestingly, rhizobox experiments have shown that detailed root distribution information may not be necessary to accurately estimate water budgets (Maan et al., 2023). This prompts the question: which variables should we prioritize observing to enhance our understanding of root zone processes?

7.2 Root zone biogeochemistry

In this opinion paper, our focus has centered on root zone hydrology, recognizing water as the crucial link among Earth system spheres. We contend that the root zone, viewed holistically, holds broad implications for biogeochemistry studies, encompassing carbon, nitrogen, phosphate, pollutants, and microbial communities, thereby influencing Earth system science on a global scale. The burgeoning field of root microbiome research in ecology is poised to significantly deepen our understanding of rhizosphere biotic processes within the root zone, their ecosystem-wide importance, and their impacts on large-scale biogeochemical cycles (McNear, 2013).

The successful integration of the holistic root zone concept into hydrology and land surface models sets the stage for incorporating more biogeochemical processes, such as carbon and nutrient dynamics, as part of an integrated system. For instance, considering carbon dynamics, plants with roots play a pivotal role in the global carbon budget by sequestering CO_2 through photosynthesis and releasing CO_2 via respiration, influencing the climate system significantly (Bian et al., 2023). Root zone dynamics are crucial for carbon sequestration strategies, particularly in predicting plant responses to elevated CO_2 levels under climate change scenarios (Nie et al., 2013; Bian et al., 2023). Among carbon storage alternatives, root zone carbon presents the highest uncertainty, yet it holds substantial potential for carbon neutrality and sequestration strategies, necessitating further experimental and modeling investigations (Friedlingstein et al., 2022).

The holistic modeling framework proves particularly adept at integrating biogeochemical processes, leveraging conceptual models as the primary approach to simulate fluxes of carbon, nitrogen, and phosphorus. This approach not only enhances our understanding of root zone processes but also contributes to advancing our capabilities in predicting and managing Earth system dynamics in response to global change (Violle et al., 2014; Reichstein et al., 2014).

7.3 Making models alive for future prediction

The call to integrate a more dynamic and "alive" root zone into Earth system models is urgent and critical for improving predictions across various disciplines (Wang et al., 2018). Static root models have shown significant discrepancies in simulating land surface water and energy dynamics (Jing et al., 2014; Cai et al., 2018a; Drewniak, 2019; Liu et al., 2020b; Zheng and Wang, 2007), largely due to their inability to capture the adaptability of root zones to changing environmental conditions. Despite pioneering efforts to incorporate dynamic root behavior into land surface and dynamic vegetation models (Wang Yuanyuan et al., 2018; Lu et al., 2019; Sakschewski et al., 2021), reductionist modeling remains dominant in Earth system models.

Currently, holistic root zone modeling primarily serves as a diagnostic approach. However, its potential lies in offering simpler and more realistic simulations. Moving forward, several approaches can enhance the integration of holistic perspectives into Earth system models:

1. Space-for-Time Exchange: Analyzing spatial transitions in ecosystems can provide insights into ecohydrological strategies and help predict hydrological responses under future climate scenarios. For instance, using methods like the mass curve technique (MCT), Singh et al. (2020) demonstrated how S_{Rmax} changes spatially with climate, offering a framework to forecast belowground and aboveground biomass variations.
2. Optimization Approach: Leveraging optimality principles to integrate water, carbon, nutrient dynamics, and vegetation responses based on ecological optimality can enhance predictions of root dynamics and their impacts on environmental changes (Schymanski et al., 2008; Wang Ping et al., 2018; Hunt et al., 2024).
3. Incorporating Physical Laws: Earth system modeling currently relies heavily on Newtonian laws of mass, energy, and momentum conservation, typical of reductionist approaches. However, broadening the scope to include additional physical laws, such as evolutionary theory and the second law of thermodynamics, can reduce parameter calibration needs and constrain model uncertainties (Savenije, 2024).

These approaches collectively aim to advance our understanding and prediction capabilities of Earth system dynamics, emphasizing the need for more integrated and comprehensive models that capture the dynamic interactions within the root zone and beyond.

7.4 Planetary stewardship

The root zone, as a critical interface between natural geosphere and anthroposphere (Fig. 3 in Steffen et al., 2020), holds profound implications for planetary stewardship and sustainable development. Human activities like agriculture, urbanization, deforestation/afforestation, land use change, the use of pesticides and fertilization profoundly impact the root zone. Understanding the root zone is pivotal for managing green water footprints, integrated water resources, and carbon sequestration (Wang-Erlandsson et al., 2022). It serves a crucial role in dividing precipitation into green water (used by terrestrial ecosystems) and blue water (available for human use), thereby influencing Earth system resilience (Falkenmark, 2000).

The management of the root zone is essential for sustaining both green and blue water within safe planetary boundaries, crucial for achieving global sustainability development goals (SDGs) such as

SDG2 (zero hunger), SDG6 (clean water and sanitation), SDG11 (sustainable cities and communities), SDG13 (climate action), and SDG15 (life on land). Proper management practices are therefore indispensable for maintaining Earth system resilience and achieving these SDGs (Stewart-Koster et al., 2023; Wang-Erlandsson et al., 2022).

Integrating the impacts of human activities on the root zone into Earth System Models (ESMs) is crucial for advancing scientific understanding, informed decision-making, and effective management of the root zone. This integration will enhance our ability to predict and mitigate the consequences of human actions on water resources, ecosystems, and global climate dynamics.

8 Concluding remarks

The root zone is the crucial element linking multi-spheres of the Earth surface system, including hydrosphere, biosphere, lithosphere, 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 “similar” terminologies, such as vadose zone, critical zone, rhizosphere, and rooting depth. For the root zone in Earth system studies, we underscored the heterogeneity within the root zone, including complexities of soil, root distribution, preferential flow, plants’ belowground zone of influence, rhizosphere and mycorrhizal fungi. However, viewing the root zone as an integrated living system, influenced by long-term self-organization and co-evolution, allows for emergent and predictable behavior, enabling simulation with simpler models, based on widely and readily available data. We advocate for a paradigm shift towards ecosystem-centered root zone studies in Earth system science, to develop ‘living’ models for more realistic future prediction, particularly in response to climate change and intensifying human activities in the Anthropocene.

Code and data availability. No code or datasets were used in this article.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Hydrology and Earth System Sciences.

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