Root zone in the Earth system

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Abstract: The ~~concept of “~~root zone~~”~~ is ~~widely used~~a vital part of the Earth system and a key element in hydrology, ecology, agronomy, and land surface ~~process studies.~~processes. However, ~~the root zone still lacks a precise~~its 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~~ varies across ~~all the spheres~~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~~, 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~~. We underscore ~~that~~ the ~~theoretical foundation~~limitations of the traditional reductionist approach ~~to understand and model the root zone is problematic due to the~~ in modeling this complex and dynamic ~~nature of root~~ zone ~~functions. We~~and advocate for a shift towards a holistic, ecosystem-centered ~~perspective, which~~approach. We argue that a holistic approach offers a more ~~realistic, simplified, and~~systematic, simple, dynamic ~~representation~~, scalable, and observable way to describing and predicting the role of the root zone in Earth system science.

1 Introduction

~~During~~Plant roots developed before leaves 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~~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 ~~showed~~indicates 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).~~

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~~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). ~~plants developed a place~~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).

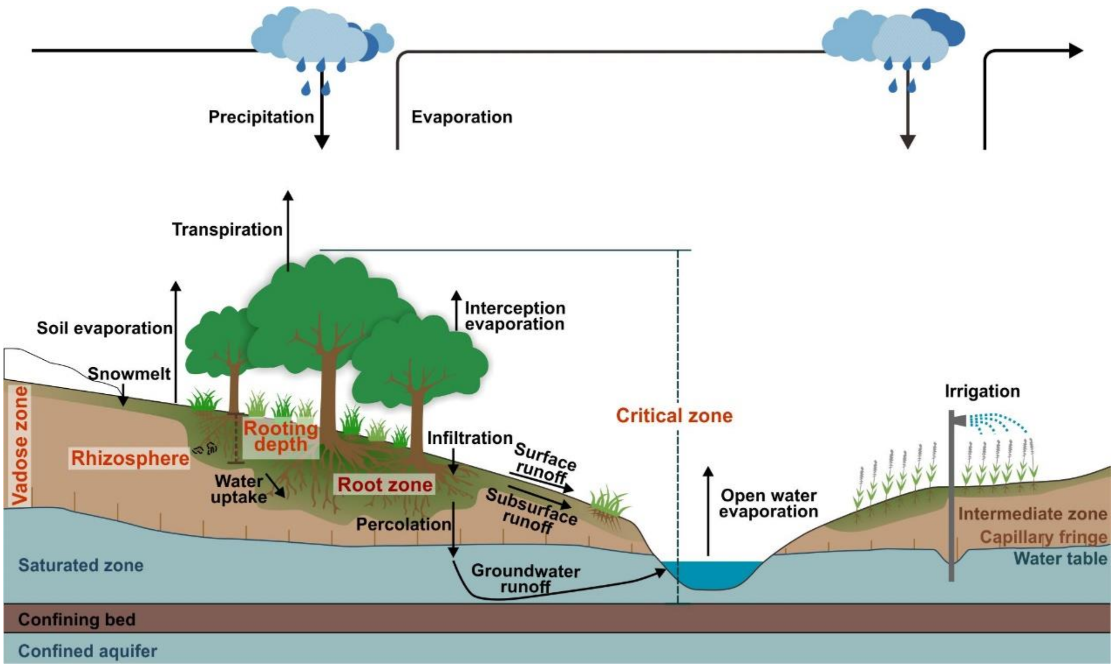


Figure 1. Schematic diagram of the root zone in terrestrial hydrological processes and atmospheric moisture cycling, showing the difference between root zone and other similar terms, such as vadose zone, rooting depth, rhizosphere and critical zone.

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 ~~the~~their environment ~~through long-term evolution, forms the substrate~~over time, constitutes the foundation of ~~the~~ terrestrial ~~ecosystem and hence~~ecosystems. As such, it is a ~~crucial element~~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).

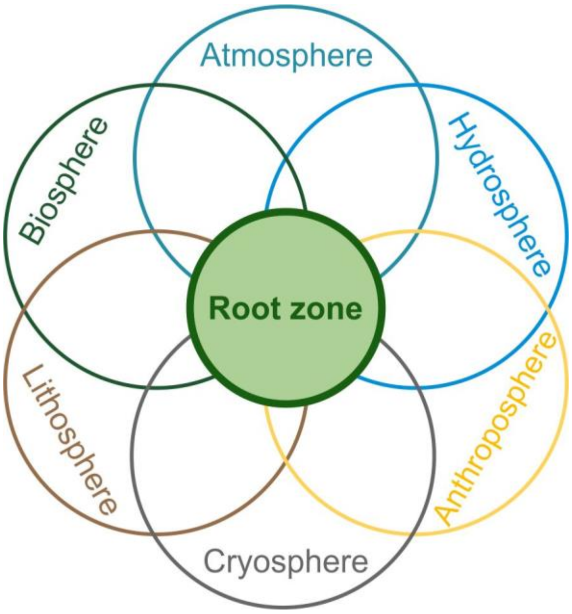


Figure 2. Root zone is the interface between hydrosphere, biosphere, lithosphere, atmosphere, cryosphere, and anthroposphere in the Earth system.

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., ~~2017). It is well demonstrated that the soil forms an ecosystem full of micro-biotic~~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). ~~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~~ 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 ~~resources.~~ 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).

~~Plants together with micro-organisms~~ 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).

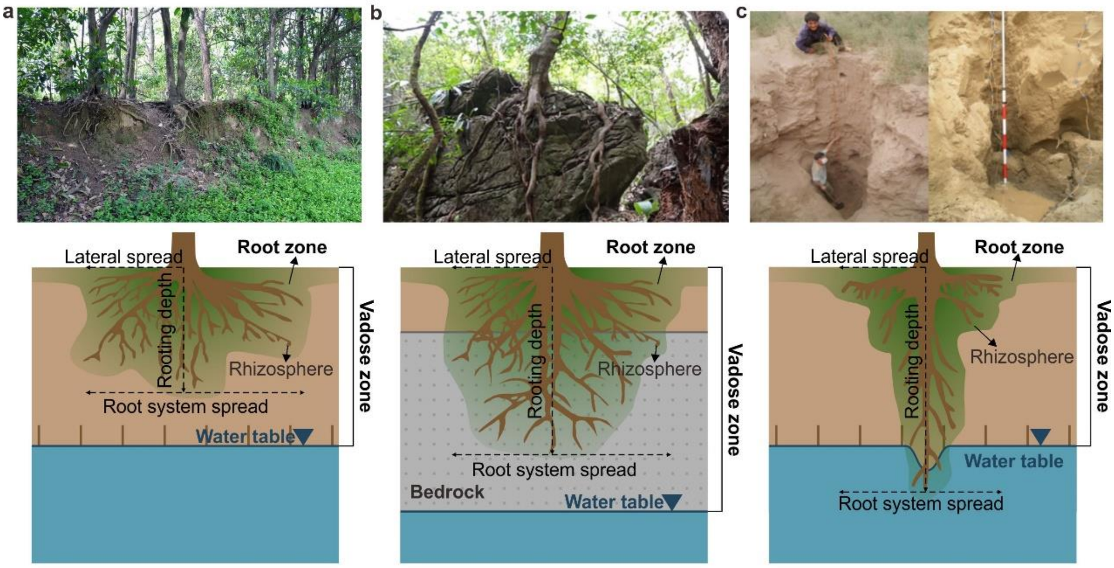


Figure 3. Root zone is different from soil depth. (**a**) is the root zone in moderate climate. Root zone is the upper area of soil; (**b**) root zone contains not only soil but also bedrock; (**c**) root zone contains unsaturated zone and groundwater, for example the phreatophytic roots in arid regions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

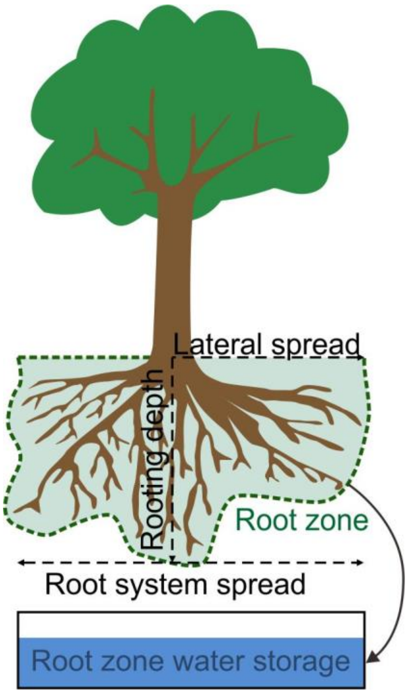
~~In the past decades, the root zone has attracted growing attention from different disciplines, including hydrology, agronomy, plant biology, soil physics, atmospheric science, and landscape engineering, for different reasons. However, there is still a lack of review on the basic concept of the root 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 (~~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).

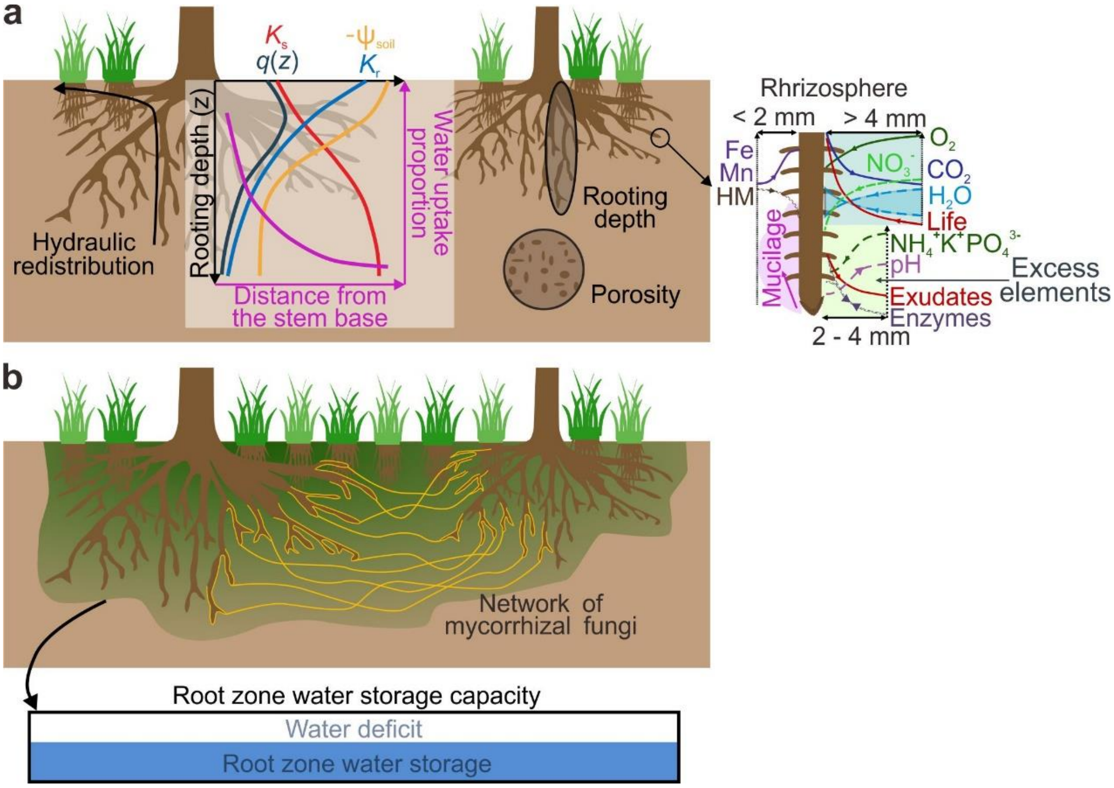


Figure 4. Comparison of reductionist (**a**) and holistic (**b**) views of root zone and root zone water storage capacity. (**a**) The reductionist perspective estimates root zone storage capacity and transpiration based on rooting depth and soil properties, assuming a static view primarily relying on 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~~)~~

~~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~~; Bachofen et al., ~~2014;~~ 2024). Top right figure shows the generalization~~Stocker et al., 2023). Similar to artificial~~

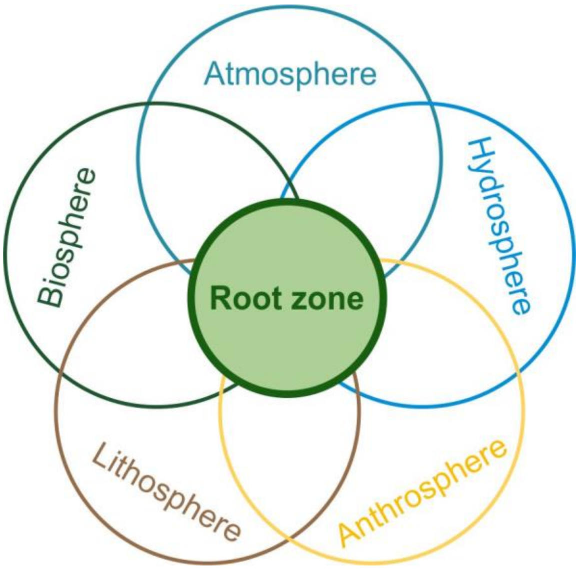
~~reservoirs designed by humans to bridge dry periods requiring investment of materials and energy, ecosystems also need carbon, energy and nutrients to develop their root zone water storage, as a buffer to overcome periods of drought. Reversely, S_{umax} is the maximum water deficit in the root zone, 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.~~

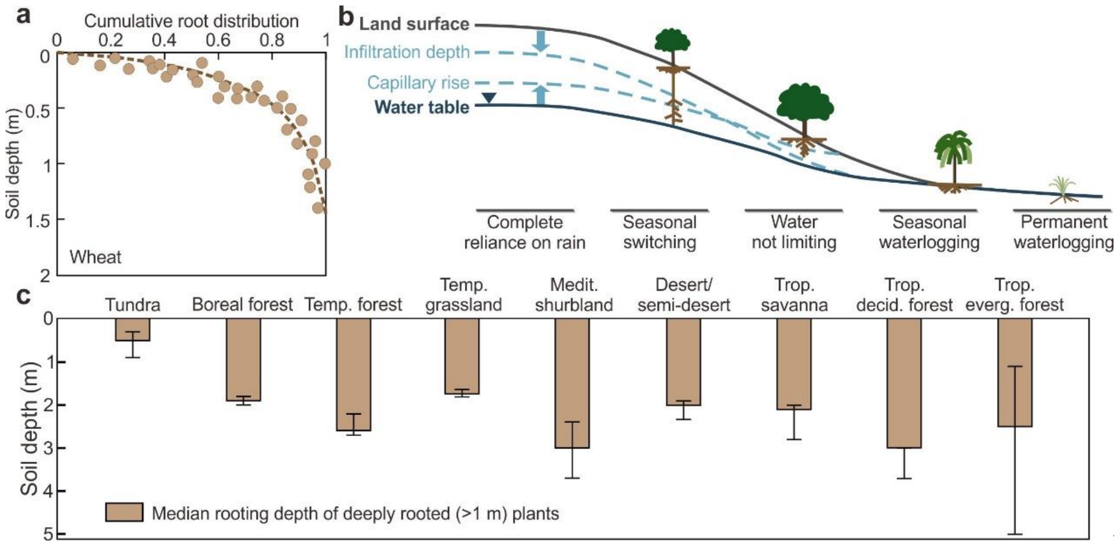
~~Measuring rooting depth and other traits accurately is one of the most time-consuming and difficult activities in ecological and agricultural research, especially if it is a field study. The methodology also varies depending on the plant community. For example, the rooting depth of grass and agricultural 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~~

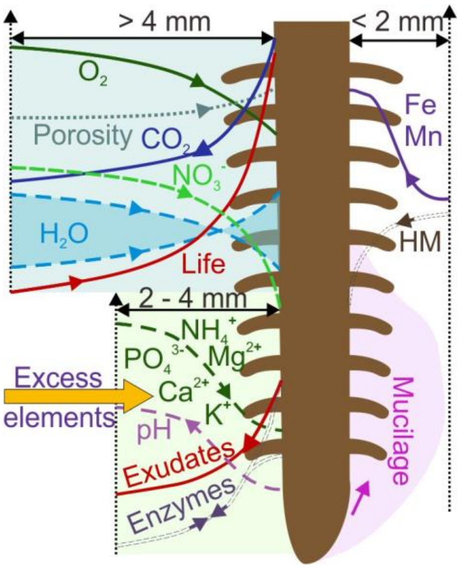
~~It is important to note that the root zone is not necessarily proportional to the rooting depth. While rooting depth only describes the vertical extension, the root zone reflects the root distribution over the entire profile. The root zone, moreover, accounts for lateral root extent and root density. 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~~).~~) (**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.

~~3.2 Root zone, lithosphere, and pedosphere~~

~~Roots as active agents~~

~~3.2.1~~ Emergent behavior 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).~~

5 ~~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 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 ~~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~~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).

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

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

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

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

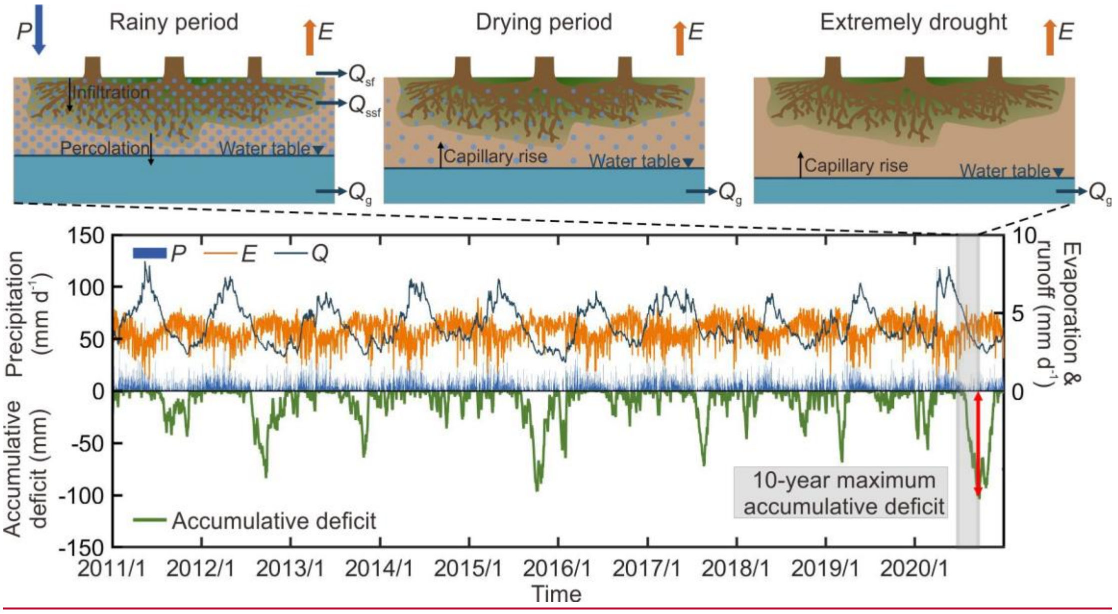


Figure 5. The dynamic change of water deficit in root zone from the wet season to dry season. On the upper panel, the conceptual illustration of the water deficit change in root zone is shown with its effect on hydrology. P and E represent precipitation and evaporation respectively. Q_{sf}, Q_{ssf} and 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).

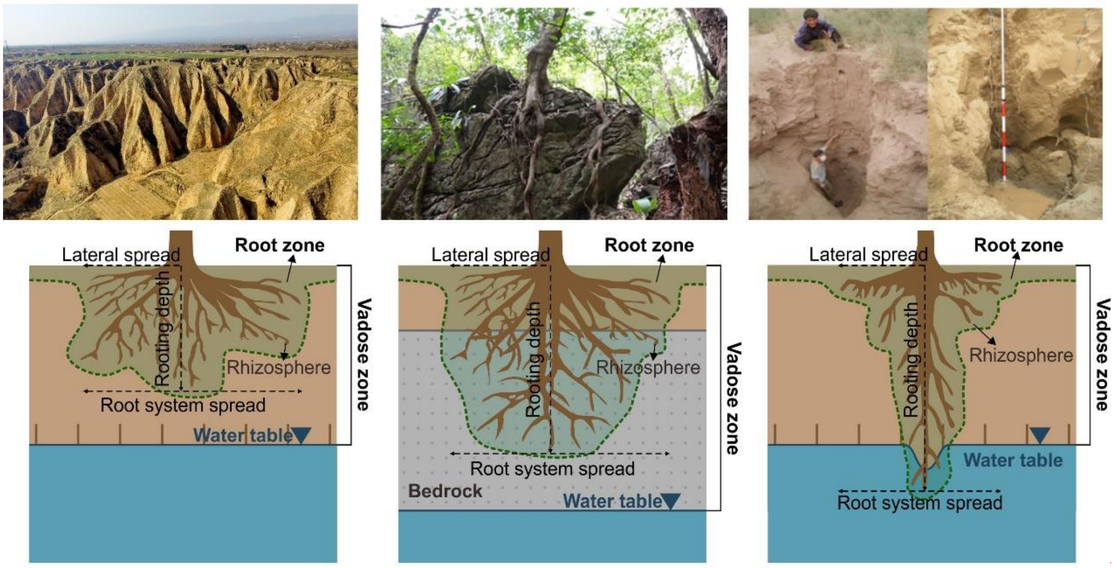
5.1.2 Climate and topography controls S_{Rmax}

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~~ 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~~ 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).~~(Beven, 2012). Root~~

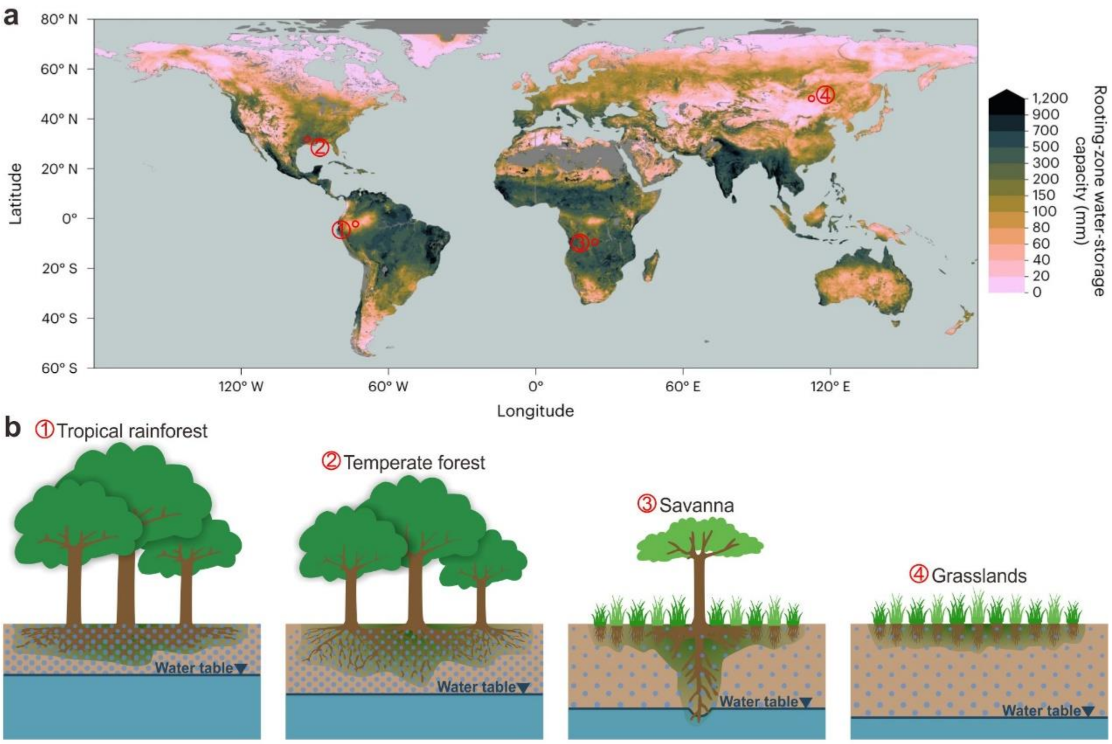


Figure 6. (**a**) The global root zone storage capacity (from Stocker et al., 2023). (**b**) The conceptual illustration of aboveground biomass and root zone in different climate zones.

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). ~~characteristics determine both. Saturation excess~~Additionally, the root zone influences evaporation and plant transpiration from groundwater sources. Surface soil and root zone drying are moderated by upward capillary flow ~~is the dominant mechanism in humid~~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). ~~. Based on this theory, there is no~~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 ~~generation when the root zone still has a moisture deficit, i.e. root zone moisture is below a critical~~ 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~~ (so called,~~ known as field capacity~~). Once the root zone moisture crosses~~ (Tromp-van Meerveld and McDonnell, 2006). Once this threshold~~,~~ is surpassed, the outflow ~~pathway becomes~~pathways are activated, ~~and~~leading to runoff ~~is generated~~generation. This mechanism is ~~also named~~often referred to as 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~~

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 ~~does~~do not ~~happen all at the same time in~~occur uniformly across an entire catchment~~. Usually~~ (Hewlett and Hibbert, 1967; Arnbroise et al., 2004; Beven, 2012; Gao et al., 2019). Typically, during the onset of wetting seasons, riparian zones ~~(close to the drain) are saturated~~near the drainage experience the critical threshold first, ~~where~~initiating saturation excess flow~~ first occurs. Subsequently, the contributed areas expand with the increase of~~. As precipitation ~~amount~~ and root zone moisture~~. Thus, the saturation excess flow mechanism is also called~~ increase, the contributing areas expand, a phenomenon known as the variable contribution area theory~~. The concept can be functioned as:~~ (Arnbroise et al., 2004). Accounting for this spatial heterogeneity of the root zone significantly improves the performance of runoff simulations (Gao et al., 2019).

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

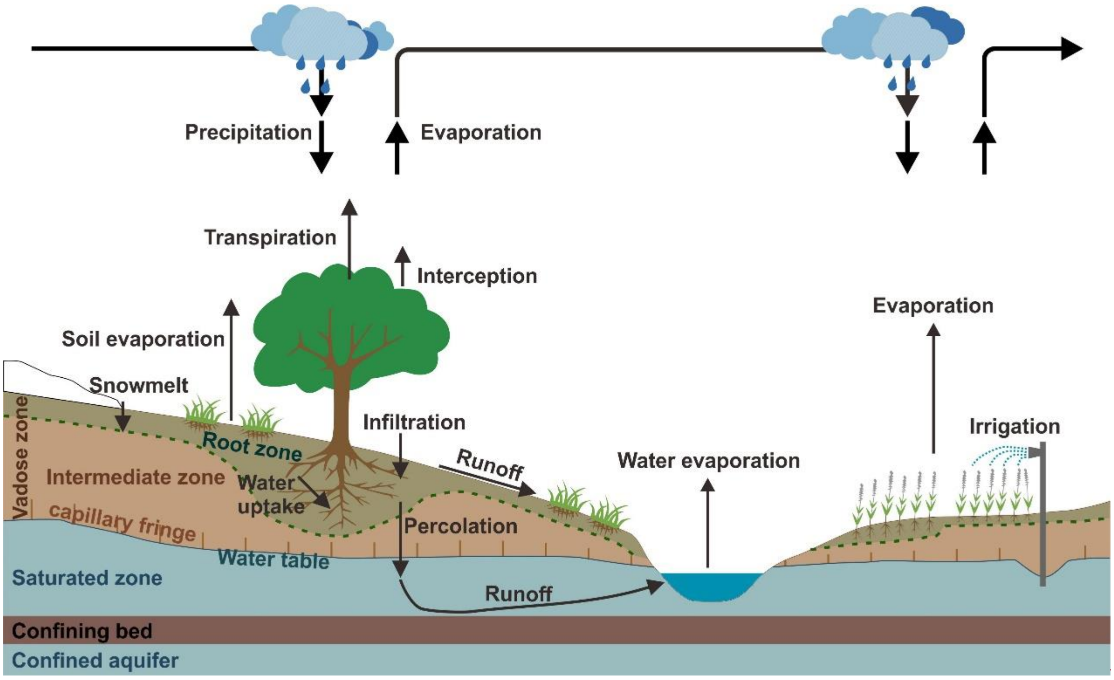
~~$Q(t) = f\big(P(t), f_\epsilon(t)\big)$ (2)~~

~~where P is precipitation intensity, f_ϵ 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,~~These conceptual models~~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.,~~ applied in global ~~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~~prediction practices, albeit with varied parameterizations 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~~terminologies (e.g. Zhao, 1992; Perrin 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~~2003; Clark et al., ~~2004). For determining the root zone storage capacity of ecosystems, the mass curve technique appeared to work well locally and globally (~~2008; Beven, 2012; Fenicia et al., 2014; 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.~~2019). 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 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~~ 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 ~~improve~~enhance water flux simulations ~~by the~~ in land surface models such as HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land ~~(HTESSEL) land surface model (e.g.,~~), resulting in improved discharge simulation correlations across different regions (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~~Moreover, the holistic approach to 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~~ is gaining traction in studies~~.~~

~~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~~water quality, solute transport, and transit times, presenting a promising new framework 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~~integrating material transport through ~~changes in vegetation composition or soil moisture, have the potential to influence carbon cycling in cold regions strongly (Wang et al., 2020).~~ the entire system (Harman and Fei, 2024).

~~4~~6 Root zone in the Anthropocene

6.1 The impacts of climate change

~~4.1~~ Climate ~~change~~

~~Climate, as the upper boundary of the root zone, has the dominant impact on~~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 ~~responds quickly~~responsive to ~~changes in~~ environmental ~~conditions. The time between photosynthesis and the~~ changes, with rapid carbon transfer ~~of carbon~~ from leaves to roots and soil organisms ~~is fast, taking~~ occurring within hours ~~in grassland or~~ to days ~~in forests. Changes in the root zone are generally cumulative, which may be introduced by slow, gradual or abrupt changes.~~ across different ecosystems (Melkikh and Sutormina, 2022).

~~Previous work demonstrated that root zone storage capacity (S_{umax}) varies spatially in response to~~The spatial variability of S_{Rmax}, reflecting climatic conditions, has been well documented (Kleidon and Heimann, 1998; Gao et al., ~~2014~~2014a; 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~~), suggesting that temporal variations in S_{Rmax} are also plausible under changing climate regimes. Local factors such as topography and groundwater dynamics further ~~validated by using the dynamic identifiability analysis (DYNIA) algorithm with a five-year moving window to explore the~~ influence root zone 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~~ , with observations indicating rapid root growth towards declining water tables in desert ~~phreatophytes~~phreatophyte vegetation (Orellana et al., 2012; Wang et al., 2018; 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).~~

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

~~4.2.0~~6.2.1 Agriculture

~~Most agricultural~~ Agricultural activities ~~are happening in~~ exert significant influence on the root zone, ~~including but not limited to~~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~~. Root zone management is essential for food production and food security. Originally,~~ predominantly occur within the ~~term "~~root zone~~" has been used in agronomy, e.g., to~~

~~assess the total amount of water~~, shaping its characteristics and ~~nutrients available for plants.~~ functionality.

Ploughing~~ as an important agriculture management ~~, a fundamental agricultural practice, ~~which greatly changes~~plays a pivotal role in altering and ~~even determines the~~determining root zone depth. ~~The~~Over time, intensive cultivation can lead to the formation of a plough pan, ~~distributed commonly from~~typically situated 15 to 30 cm ~~beneath~~below the soil surface~~, caused by long-term cultivation, is formed under the root zone with a high ~~ in clay~~ content (Li et al., 2019). ~~-rich soils. This ~~relatively impermeable~~compacted layer ~~limits~~acts as a barrier beneath the root zone, limiting water percolation and ~~constrains~~restricting root growth ~~in~~to the relatively ~~small~~shallow soil layer above ~~the plough pan. ~~it (Li et al., 2019). In such ~~cases, it is indeed~~scenarios, the moisture holding capacity of the topsoil ~~that determines~~becomes critical in defining the root zone storage capacity.

In ~~cropland, where ~~irrigation ~~provides an extra~~agriculture, where additional water ~~supply~~is supplied to the root zone during dry ~~seasons, the root zone water storage capacity is~~periods, the S_{Rmax} often becomes smaller ~~than under~~compared to natural conditions with similar ~~climate conditions~~climates (Xi et al., 2021; Hauser et al., 2022; van Oorschot et al., ~~2023). Due to ~~2024). Studies indicate that due to irrigation ~~(not considering ~~practices (excluding considerations of climate change impacts), rooting depth ~~was~~can be reduced by approximately 5%, ~~or ~8 cm, or~~equivalent to an approximate loss of ~~~~~8 cm in depth or about 11,600~~ km^3~~ km^3 of rooted volume (Hauser et al., 2022). ~~In~~At a global scale~~ study, when considering irrigation as an extra water supply, S_{umax} in cropland was found to consistently~~, 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., ~~2023~~2024).

6.2.2 ~~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.,~~

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~~2014). Thus, agricultural root zone management is a pivotal issue for food security, human health, water resources management, and environmental protection (Gu~~ (Nijzink et al., 2016). Conversely, ~~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~~ often see root depths deepening by ~~~~~approximately 38~~-~~ cm compared to the previous dominant vegetation (Hauser et al., 2022).

The root ~~zone plays an essential~~zone's role ~~in~~extends to evaluating the ~~effects~~outcomes of large-scale ecological initiatives. For example, projects~~. For instance, the “~~ like China's "grain-to-grass~~”~~" and ~~“~~"three norths afforestation projects~~” in China,~~" have ~~been greatly~~proven beneficial for soil ~~and water retention, biodiversity~~ conservation, flood control, biodiversity enhancement, and carbon sequestration (Chen et al., 2019; Li et al., 2021). ~~But~~However, these ~~projects still face great~~initiatives have also increased water consumption through evaporation, posing challenges ~~in~~for water management ~~of these~~in arid regions~~,~~ where ~~severe competition exists between society's water demand and~~societal water demands compete with ecosystem services (Feng et al., 2016). ~~Moving~~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~~, means bringing~~ involves incorporating both blue- and green-water~~, –~~ considerations—surface and groundwater~~, in the same —~~into a unified framework (Falkenmark, 2000). Root zone moisture ~~forms the essential link between~~plays a pivotal role in linking land surface fluxes, water resources, soil erosion, and carbon sequestration, ~~determining~~ thereby influencing the success and sustainability of ~~these grand~~such ambitious ecological 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~~

6.2.3 ~~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~~

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

There is ~~also an increasing~~growing interest in ~~using~~leveraging vegetation to manage ~~catchment and regional~~ hydrology ~~(Palmer et al., 2015), especially~~ in ~~the~~ urban ~~environment, as~~ environments, exemplified by ~~the “~~initiatives like China's "Sponge City" initiative~~” in China~~ (Xia et al., 2017). The root zone ~~is the largest and most widespread~~ "acts as a natural sponge" in larger natural landscapes such as forests and ~~grassland at large scale, whereas~~grasslands, while green ~~roof~~roofs and ~~garden provide a “sponge” at city~~urban gardens serve as smaller-scale sponges within cities and ~~block scale~~neighborhoods. Increasing ~~S_{umax}~~the S_{Rmax} has the potential to enhance flood prevention, improve ~~flood prevention,~~ water purification, ~~relieving~~mitigate the urban heat island effect, and enhance the aesthetic value ~~in the~~of urban ~~environment.~~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.

~~4.4~~7.4 Planetary stewardship

~~As the key linkage~~The root zone, as a critical interface between ~~the~~ natural geosphere and ~~the~~ anthroposphere (~~Figure 1, and~~ Fig. 3 in Steffen et al., 2020), ~~understanding the root zone has broad relevance to~~ holds profound implications for planetary stewardship~~, such as~~ 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 ~~footprint~~footprints, integrated water resources ~~management~~, and carbon sequestration (Wang-Erlandsson et al., 2022). ~~The root zone plays~~It serves a ~~key~~crucial role in ~~partitioning~~dividing precipitation into ~~the invisible~~ green water (used ~~for~~by terrestrial ~~ecosystem~~ecosystems) and ~~visible~~ blue water (~~usable~~available for human ~~society) (~~use), thereby influencing Earth system resilience (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~~

The management of the root zone is essential for sustaining 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~~, crucial for achieving global sustainability development goals (SDGs~~), including but not limited to SDG1 (no poverty),~~) such as 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). 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).

~~5 Root zone estimation approaches~~

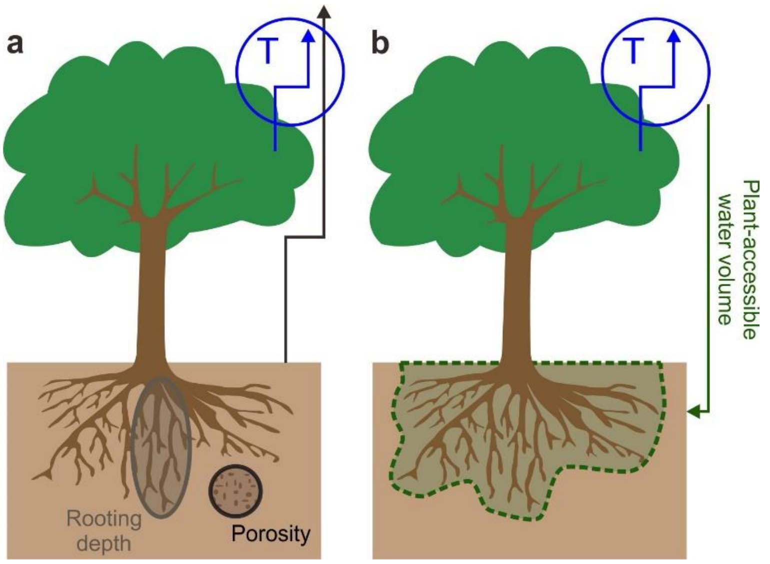
~~5.1 Root zone water storage capacity ≠ rooting depth × soil water holding capacity~~

~~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~~ 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

~~(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 hydrosphere, 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~~“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.

~~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.~~

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.

Acknowledgements. This research has been supported by the National Natural Science Foundation of China (grant no. 42122002 and 42071081).

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