

Plant Roots and Ecosystem Stability: A Structured Review

Wenhui Li

Biology, College of Liberal Arts and Sciences, Iowa State University, Ames Iowa, 50014, The United States
wenhuili@iastate.edu

Abstract:

Plant roots are multifunctional organs that not only anchor plants but also regulate water and nutrient flow, construct soil structure, and influence biogeochemical cycles. Root characteristics include systemic structure (such as taproot, fibrous roots, and basal roots), tissue anatomy (like epidermis, cortex, endodermis, and xylem/phloem), and rhizosphere processes (such as root hairs, air cavities, exudates, and mycorrhizae). These characteristics affect ecosystem functions, including water redistribution, soil aggregate formation, carbon sequestration, and resilience to disturbances. However, the complexities of the underground and methodological differences have historically made generalization difficult. This paper explores the impacts of root morphology and function on ecosystem stability, including root classification, specialized structure, and the role of roots in processes such as water and nutrient uptake, plant-microbe interactions, soil structure, and carbon cycling. And it also discusses the contributions of roots to ecological stability and resilience, such as controlling erosion, mitigating drought and nutrient changes, and promoting recovery, while identifying current challenges and methodological needs. The results indicate that root morphological diversity and functional differentiation significantly influenced water redistribution, soil aggregation, and carbon sequestration. Rhizosphere microorganisms, through interactions with roots, promoted nutrient acquisition and enhanced ecosystem stability. Roots also played a crucial role in preventing soil erosion and mitigating drought.

Keywords: Root morphology, Water redistribution, Rhizosphere microorganisms, Soil aggregation, Carbon sequestration

1. Introduction

The root systems are a vital interface between plants and their environment, serving as conduits for water and nutrient absorption and playing an “engineering” role in key processes related to soil, water, and biogeochemical processes. In recent years, with the rapid development of root functional ecology, it has become increasingly clear that root diversity is not only essential for plant growth but has a profound impact on the productivity and stability of ecosystems. This paper explores the relationships between root morphology, anatomy, and symbiotic relationships, and their roles in regulating ecosystem functions like erosion control, hydraulic redistribution, nutrient capture, and mineral-associated organic carbon (MAOC) formation. Despite extensive research on root function, the ecological role of roots remains incompletely understood due to the complexity of underground systems and the diversity of research methods. Besides, it examines root morphological diversity and functional classification, focusing on the impacts of roots on water and nutrient acquisition, interactions with microorganisms, soil structure changes, and carbon sequestration. Furthermore, the paper analyzes the importance of roots in responding to ecological disturbances such as drought and erosion, highlighting their potential applications in ecological restoration and climate adaptation. Through an in-depth literature review and analysis, this paper integrates the latest research findings on root morphology, function, and rhizosphere microbial interactions, explores the role of roots in ecological processes, and offers insights and guidance for soil management, ecological restoration, and climate change adaptation.

2. Root System Classification and Morphological Diversity

This chapter presents an analysis of the diversity and structural organization of root systems, emphasizing the impact of various root types and anatomical characteristics on plant strategies for resource acquisition and adaptation to environmental conditions. By delineating the primary forms of morphological and functional variation, this section lays the groundwork for comprehending the influence of root traits on ecological dynamics.

2.1 Taproot, Fibrous, and Adventitious Roots

Root systems can generally be classified into taproot type, fibrous root type and epiphytic root type. Taproot systems have distinct taproot axes that can penetrate deep into the soil, facilitating access to deep groundwater and nutrients, and then enhancing the plant’s ability to survive in arid or infertile environments. The fibrous root system is mainly distributed in the topsoil, forming a dense root network. It can not only quickly absorb surface water and nutrients, but also enhance the stability of soil structure and prevent soil erosion. Epiphytic roots can grow in atypical locations (such as stems, leaves or mechanically damaged areas), giving plants adaptability and growth plasticity under soil cover, flooding or mechanical pressure [1]. From an ecological and evolutionary perspective, these types of root systems roughly correspond to the differences in life histories between dicotyledonous and monocotyledonous plants, as well as the continuum of adaptations from terrestrial to aquatic habitats. And in water or wet environments, plants with aerenchyma tissue or pneumatophore-like structures can exchange gases more efficiently, thereby enhancing their survival in oxygen-deficient soils or flooded conditions [1].

2.2 Functional Pools and Root Orders

Recent research has shown that the concept of “root length less than 2 mm” is incomplete when considering only root structure, leading to the emergence of the concept of the functional root system. This is a part of the general root system, which is further divided into two parts: haustoria and suckers. Suckers are generally characterized by small diameter, short lifespan, and many branches. Their main drawbacks are poor water absorption and limited water absorption capacity. Suckers grow and regenerate quickly and are closely intertwined with mycorrhizal fungi. However, plants have strong selective capture capabilities, which greatly impact soil circulation. In contrast, transport roots are relatively robust, have a longer lifespan, and fewer branches. Their main function is to transport water and nutrients from the absorbing roots to the stems and leaves, and to provide structural support for the plant. They grow more slowly and have a longer renewal cycle, acting more like the “skeleton” of the root system. This functional classification not only better aligns with the economic strategies of plants regarding nutrients and water, but is also highly correlated with mycorrhizal dis-

tribution areas, carbon input, and nutrient flow patterns [2]. This reclassification can improve turnover estimates, allocation modeling, and cross-study synthesis [2].

2.3 Components of Roots and Specialized Structures

Roots are composed of various tissues such as the epidermis, cortex, endodermis, periderm, xylem, and phloem. The root epidermis and root hairs greatly increase the contact area with the soil, thereby improving the efficiency of water and nutrient absorption. The cortex not only plays a role in storing nutrients and water, but also forms aerenchyma, an aerated structure that reduces the cost of root construction and maintenance and promotes oxygen transport within the root, especially important under flooded or compacted conditions. The endodermis controls efflux through its Casparian strip, ensuring selective entry of water and solutes into the xylem. The periderm is the starting point for lateral root development, supporting root expansion and soil exploration. The xylem and phloem are responsible for long-distance transport of water, solutes, and signals within the root and exhibit functional plasticity in response to environmental stresses. Under drought or saline-alkali stress, these tissues can minimize the effects of stress through structural adjustments or metabolic optimization while maintaining effective absorption functions [1,3].

The specialized structure includes root hairs and air cavities. Root hairs are slender structures that extend from epidermal cells, significantly increasing the absorption area and helping to acquire phosphorus and trace elements. Air cavities are gas-filled gaps formed in the cortex, which not only support the transport of oxygen in flooded or compacted soil, but reduce the metabolic consumption per unit root length, enabling the root to explore the soil more extensively with limited carbon resources, thereby enhancing the plant's adaptability in complex environments [3].

3. Roots and Ecosystem Functions

This chapter provides a summary of the essential ecological functions of roots, concentrating on their roles in the acquisition of resources, their interactions with soil microorganisms, and their contributions to soil structure and carbon cycling. It underscores the manner in which

root-driven processes collectively influence ecosystem functioning and biogeochemical dynamics.

3.1 Water and Nutrient Uptake Mechanisms

Water uptake reflects gradients in water potential and aquaporin regulation at the root-soil interface. At night, when evapotranspiration demand is low, the direction of water flow may reverse, resulting in hydraulic redistribution. This means that dry topsoil can obtain moisture from wetter deeper soils, a phenomenon that has significant implications for ecosystems [4,5]. Existing research shows that the hydraulic redistribution in various ecosystems is typically 0.04-1.3 mm H₂O d⁻¹ [5,6]. These fluxes allow for shallow microbial activity, nutrient mineralization as well as support to neighboring plants during droughts [4,5]. In addition, root morphology and chemical characteristics (such as root length and branching pattern) are closely related to nutrient acquisition through root exudates and rhizosphere pH. In phosphorus-limited systems, high specific root length (SRL) absorbing roots are typically dominant, while arbuscular mycorrhizae dominate these environments. Ectomycorrhizae (ECM) help plants acquire organic nitrogen and influence community structure and biogeographical patterns [7,8].

3.2 Root-Microbe Interactions

The root system attracts microorganisms by secreting sugars, amino acids, organic acids, phenolic substances, and polysaccharide mucus, thereby altering resource stoichiometry and enzyme activity. Plants can alter the types of secretions to guide microbial communities to perform specific functions, such as phosphorus dissolution or pathogen inhibition [9-11]. As root exudates are rapidly renewed and easily adsorbed, in situ quantification is challenging, so many studies have also focused on the quality of exudates to determine carbon fate [11].

Mycorrhizal networks broaden the functional root system and influence interactions between plants. And recent studies suggest that different types of mycorrhizae control seedling establishment and coexistence processes through stable and balanced mechanisms such as nutrient allocation, feedback of soil pathogens, and provision of differentiated benefits [7]. These dynamics have a strong impact on community assembly as well as ecosystem processes [7,8].

3.3 Soil Structure Improvement and Carbon Sequestration

3.3.1 . Soil Aggregation and Structural Stability

Roots, hyphae, and mucilage can physically trap soil particles and release sticky substances, thereby maintaining the stability of soil structure from micro-aggregates to macro-aggregates. And it is found that arbuscular mycorrhizae bacteria significantly promote soil aggregation at different scales, altering pore connectivity and water flow [12]. This improved soil structure not only enhances air circulation and water storage capacity but improves nutrient retention efficiency, while providing a more stable habitat for soil microorganisms, thus further promoting nutrient cycling and ecosystem function. In addition, a more stable soil aggregate structure can enhance soil erosion resistance and maintain the physical integrity of soil under extreme dry and wet conditions.

3.3.2 . Contribution of Roots to Carbon Sequestration

Due to their proximity to soil minerals and the enhancement of microbial processing, root-derived materials, including biomass, exudates, and mycorrhizal residues, can generate stable MAOC more effectively than leaf litter. Field experiments estimate that live root inputs are about 2-13 times more efficient than litter in forming MAOC and particulate organic carbon (POC) [13]. The MEMS framework suggests that microbially processed readily degradable carbon inputs can be further stabilized into MAOCs in the presence of adsorption capacity [14]. Then, the fate of exudate carbon depends on soil environmental conditions (such as texture, Fe/Al oxide content) and aggregation state, i.e., carbon may be released by respiration (priming effect) or fixed and retained (stabilization) [13,14]. Furthermore, the near-source input and continuous release of root-derived carbon can form a stable carbon pool in the soil microenvironment, improve soil structure, and provide a continuous energy supply for the microbial community.

4. The Role of Roots in Ecosystem Stability and Resilience

This chapter delineates the significant role that roots play in ensuring ecosystem stability and resilience, underscoring their critical function in mitigating soil erosion, alleviating environmental stresses, and facilitating ecological

recovery. It illustrates the pivotal importance of below-ground characteristics and processes in sustaining ecosystem integrity in the face of changing conditions.

4.1 Soil Erosion Prevention

Dense root systems on the surface can enhance soil cohesion and shear strength, thereby reducing the likelihood of soil particles being stripped and transported in surface runoff. Empirical models indicate that soil stripping decreases exponentially with increasing root mass or root length density [15]. Plants with high tensile strength and fibrous root structures are best suited for bioengineering on slopes and in waterways [15,16]. Furthermore, root systems not only effectively prevent soil erosion by improving soil structure but also enhance soil moisture retention, especially after heavy rainfall, helping to reduce the erosive effect of water flow on the soil surface. The role of roots in combating erosion is multifaceted, including mechanical anchoring and enhancing soil cohesion by promoting the accumulation of soil organic matter.

4.2 Drought Buffering and Nutrient Retention

Deep or dual-structured root systems can utilize water below the surface and replenish the upper soil through hydraulic redistribution, promoting nutrient cycling and helping adjacent shallow roots acquire water during droughts [4-6]. By maintaining “hotspots” of microbial activity and nutrient mineralization, roots can also indirectly reduce nutrient loss and maintain ecosystem productivity under stress conditions [8]. Furthermore, the hydraulic redistribution of water by the root system not only buffers water replenishment but also regulates the spatial distribution of soil moisture, enabling plants to rely on groundwater and deeper water sources during prolonged droughts, thus preventing plant death due to surface soil dehydration. At the same time, the root system’s regulation of water and nutrients contributes to the stability of the microbial community, thus improving soil nutrient mineralization.

4.3 Support for Ecological Succession and Restoration

Underground biodiversity and mycorrhizal strategies can influence plant colonization, primacy, and competition hierarchy. In ecological restoration, rebuilding mycorrhizal networks and selecting root combinations with comple-

mentary characteristics (such as a mixture of deep roots and fibrous roots) can accelerate soil structure recovery and stabilize the carbon pool [8,12,14]. Furthermore, the role of root systems and mycorrhizal networks in ecological restoration extends beyond the restoration of physical soil structure; it also includes boosting biodiversity and increasing plant competitiveness. By selecting appropriate plant communities and mycorrhizal types, symbiotic relationships between species can be promoted, thereby accelerating the self-repair process of the ecosystem. In addition, mycorrhizal networks help to accelerate the storage of soil organic carbon, and improve the soil's long-term carbon sequestration capacity.

5. Current Challenges (Methodological Issues)

The opacity and heterogeneity of soil make subsurface research more challenging. A key issue is the differing definitions of "fine roots," leading to increased variability between different studies. Thus, classification methods based on root hierarchy and function have been proposed, which can reduce bias between different studies [17]. Another challenge is sampling depth and design. The failure of shallow sampling to account for deep roots, which are critical for hydraulic redistribution and soil carbon input, may cause misunderstandings of soil dynamics [5]. Moreover, quantifying root exudates is also a technical challenge. Due to the rapid turnover and adsorption effects of exudate fluxes, the flow of exudates captured in situ is often disrupted, affecting the accuracy of the results. Linking these exudates to the formation of MAOC remains a frontier research area [13,14]. To address these issues, standardized sampling methods and more efficient tracking tools are particularly important, such as shared databases, sampling protocols with defined depths, and more precise carbon tracking markers [1].

6. Conclusion

This study indicates that root characteristics and symbiotic relationships determine the ecosystem stability from root hairs to the watershed. Specifically, the diversity of root morphology (taproot, fibrous roots, epiphytic roots) is closely related to hydraulic redistribution (HR), soil mechanics (aggregation, reinforcement), and carbon pathways (MAOC formation). Recently, the emergence

of feature-based frameworks and consensus methods has enabled us to predict when and where root systems can alleviate drought, resist erosion, or build sustainable soil carbon. To achieve this, coordinating the measurement of features has become a priority, while simultaneously resolving complex exudates in field soils and routinely representing HR and mycorrhizal strategies in land surface models. This study provides a basis for translating subsurface biology into nature-based solutions for climate adaptation, watershed protection, and resilience remediation.

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