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Plant root-mediated carbon sequestration and nutrient cycling in grassland ecosystems under land use and climate change

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ABSTRACT

Plant roots are fundamental to grassland ecosystems, driving carbon sequestration, nutrient cycling, and soil stabilization. This review examines the mechanistic roles of plant roots in regulating Carbon (C) and nutrient dynamics under shifting land use and climate conditions. By integrating insights from root physiology, soil biogeochemistry, and ecosystem ecology, we explore how root traits morphology, architecture, and exudation govern belowground C allocation, nutrient acquisition, and soil organic matter formation in response to environmental change. We analyze the effects of land use practices, including grazing, cultivation, and land conversion, on root function and ecosystem services, emphasizing the necessity of sustainable management strategies to maintain these critical processes. Additionally, we assess climate change-induced alterations, such as shifts in precipitation patterns, temperature extremes, and elevated atmospheric CO_2, and their consequences for root-mediated C and nutrient fluxes. Finally, we highlight research gaps and management strategies essential for sustaining root-driven ecosystem functions under accelerating global change. This review underscores the pivotal role of plant roots in enhancing the resilience and sustainability of grassland ecosystems amidst ongoing environmental challenges.

1. Introduction

Grassland ecosystems cover approximately 40 % of the Earth's terrestrial surface and serve as major reservoirs of organic Carbon (C) and essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Liu et al., 2023). These ecosystems play a critical role in global biogeochemical cycles, biodiversity conservation, and climate mitigation. This review provides a timely and scientifically grounded synthesis of current knowledge on the interplay between grassland management practices and ecosystem functioning, emphasizing their implications for climate mitigation, biodiversity preservation, and the restoration of soil health.

Among the ecological drivers shaping grassland resilience, plant roots play a central role but are often underexplored in broader ecosystem assessments. Roots serve as the primary interface between vegetation and soil, governing essential processes such as water uptake, nutrient acquisition, and soil C input through root turnover and exudation (Pathan et al., 2020; Paul, 2016). Their structural and functional traits root depth, architecture, exudation chemistry, and lifespan are key determinants of belowground ecosystem processes and are tightly linked to soil microbial activity and nutrient availability (Freschet et al., 2021).

Land use change, including intensive grazing, cropland expansion, and urban development, significantly alters root traits, thereby influencing C and nutrient dynamics in soils (Tian et al., 2023). These alterations can lead to reduced root biomass, impaired root distribution, and compacted soils, which together constrain the soil's capacity to store C and recycle nutrients efficiently (Ding et al., 2021; Ma et al., 2021). Furthermore, these anthropogenic changes compromise the provisioning of critical ecosystem services such as soil stabilization, productivity, and water regulation.

Simultaneously, climate change exerts profound effects on root development and functioning through temperature shifts, altered precipitation patterns, and increased atmospheric CO_2 concentrations

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(Sümmerer et al., 2025). These drivers influence root growth, turnover rates, and interactions within the rhizosphere (Chen et al., 2022). For instance, elevated temperatures can stimulate root respiration and microbial decomposition, potentially increasing nutrient mineralization but also accelerating C loss from soils (Dolezal et al., 2021). Droughts or erratic rainfall patterns force adaptive changes in root morphology and distribution to maintain water uptake, which in turn modulates nutrient cycling and ecosystem stability (Wang et al., 2023).

An increasing body of evidence underscores the significance of deep-rooted species and diverse root architectures in enhancing long-term soil C storage and promoting beneficial soil microbial communities (Dijkstra et al., 2021; Lv et al., 2023a). Root exudates fuel microbial activity that facilitates the decomposition of organic matter and solubilization of nutrients, such as P and N, supporting ecosystem productivity (Kuyper and Jansa, 2023; Zia et al., 2021). These root–microbe interactions are pivotal for sustaining grassland health, particularly under environmental stress.

Despite their importance, substantial gaps remain in our understanding of root-mediated ecological processes under simultaneous land use and climate stressors (Mehra et al., 2025). The functional diversity of root traits and their responses to combined pressures are still poorly characterized across grassland types and climatic regions. This hinders the development of predictive models and management strategies that can optimize root function for sustainable C and nutrient management. A more integrative approach linking root biology, soil ecology, and landscape management is urgently needed to advance both ecological theory and practical restoration strategies (Chapman et al., 2012; Labeyrie et al., 2021).

To address these knowledge gaps, this review aims to investigate how plant root traits influence C sequestration and nutrient accumulation in grassland ecosystems under land use change and climate stress. Specifically, it synthesizes recent evidence on how root architecture, depth, biomass, and biological interactions affect soil organic carbon (SOC) and nutrient dynamics. To aid comparative understanding across diverse ecosystems, Supplementary Table 1 summarizes key cited studies, including their geographic location, climate zone, type of intervention, and ecological outcomes related to root-mediated C and nutrient processes.

To ensure a rigorous and comprehensive synthesis, we conducted a structured literature review using databases such as Web of Science, Scopus, and Google Scholar. We prioritized empirical and review papers from the last two decades, focusing on studies that link root traits to ecosystem processes in grasslands affected by environmental change. Fig. 1.

2. Plant root mechanisms for C and nutrient accumulation

Plant roots are central to grassland ecosystems' C and nutrient dynamics, mediating a wide range of belowground processes that govern soil health, ecosystem productivity, and resilience. These mechanisms are vital for understanding how plants acquire, store, and redistribute essential resources, particularly in response to changing environmental conditions. This section explores the key root traits and processes that drive C sequestration, nutrient cycling, and soil stabilization, highlighting their importance for ecosystem functioning.

2.1. Root morphology and architecture

Root morphology and architecture refer to the structural traits of plant root systems, including root length, density, diameter, branching patterns, and depth distribution (Ramachandran et al., 2025). These physical characteristics are critical for determining how efficiently plants access soil resources such as water and nutrients (Freschet et al., 2021). Root morphology influences the horizontal and vertical extent of a plant's ability to explore the soil environment, affecting nutrient uptake, plant anchorage, and stability. Root morphology (e.g., root diameter, hair density), architecture (e.g., rooting depth, lateral spread), and exudation patterns play distinct and complementary roles in mediating belowground ecological processes. Fine root structures with high surface area enhance nutrient and water uptake by intensifying

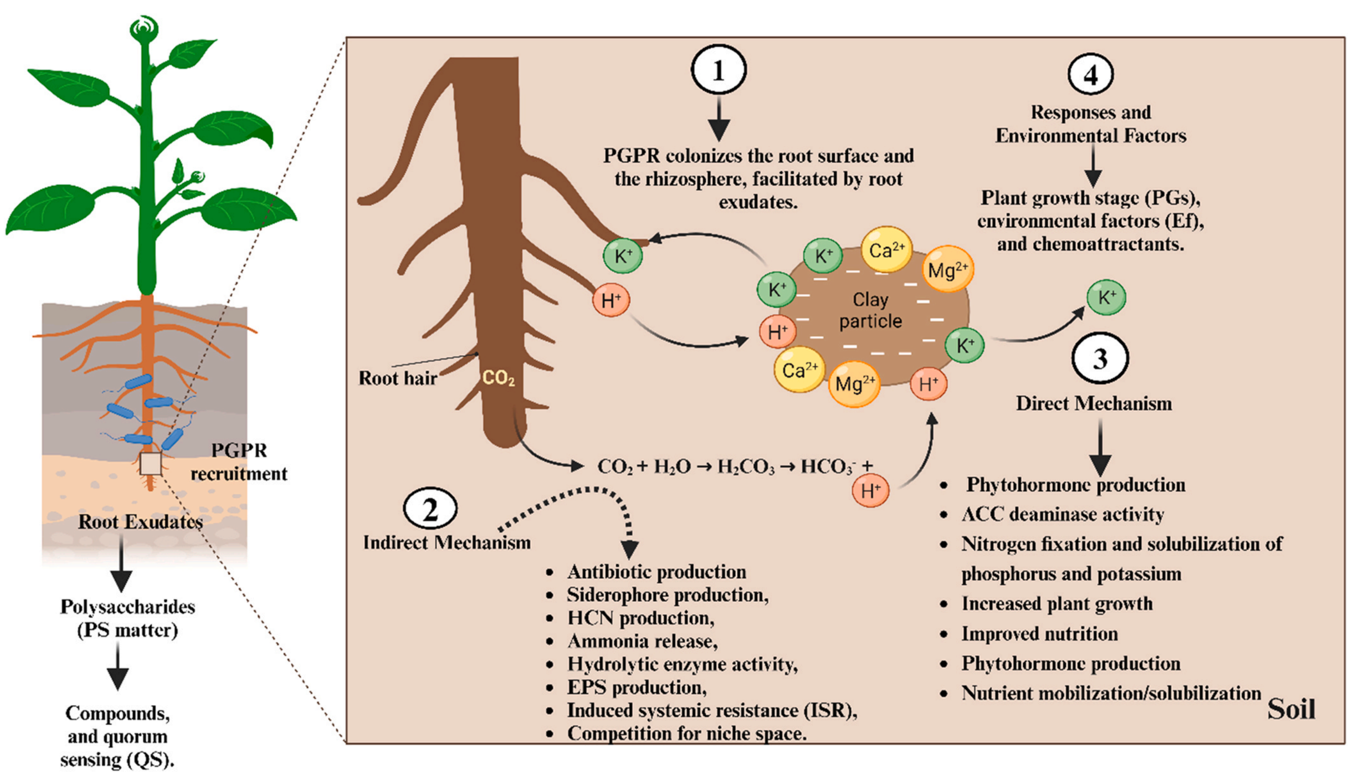

Fig. 1. Root architecture strategies in grassland plants and their role in mediating microbial interactions through root exudates.

contact with the soil matrix (Negi et al., 2025). Deep and laterally extensive root architectures increase subsoil exploration and promote vertical redistribution of water and nutrients Zhao et al., (2024). Furthermore, root exudatesccomprising organic acids, amino acids, and secondary metabolitescstimulate microbial activity and enzymatic functions, which are critical for N-mineralization, P-solubilization, and microbial C-use efficiency (Lv et al., 2023a). These exudates also act as precursors for soil aggregation by serving as energy sources for microbes that produce extracellular polymeric substances (Kuyper and Jansa, 2023), ultimately improving soil structure and enhancing C stabilization.

Grassland plants exhibit various rooting strategies, which can be broadly categorized into deep-rooted and shallow-rooted species, depending on their evolutionary adaptations to different environmental conditions (Kong et al., 2017). The diverse root structures of various plant types showcase how root depth and morphology vary across species, from deep-rooted trees to shallow-rooted grasses. Each plant's root system is critical in nutrient uptake, C storage, and soil stability, highlighting ecosystem functional differences. Understanding these differences is essential for assessing how land use and climate change impact C accumulation and nutrient cycling in grassland environments (Fig. 2).

In contrast, shallow-rooted species, including many grasses and herbs, maximize their resource capture by spreading their roots horizontally near the soil surface, optimizing nutrient uptake from surface soils (Francis et al., 2023). Root diameter is vital in interacting with soil particles and microbial communities. Fine roots, with smaller diameters, are typically more efficient at nutrient absorption due to their increased surface area and proximity to soil microbial activity (Adeniji et al., 2024).

Conversely, thicker roots serve primarily for support and nutrient transport (Kong et al., 2017). The balance between these roots within a plant's root system reflects its strategy for maximizing nutrient uptake and physical stability. Roots improve soil physical stability through aggregation and reduced erosion. Their penetration creates pore networks that promote water infiltration and reduce compaction. Root exudates also act as biological adhesives, promoting the formation of stable soil aggregates. Zhao et al., (2024) found that deeper rooting systems in semi-arid regions increased macroaggregate formation and reduced erosion risks under variable precipitation regimes. Zhang et al., (2025) reported that fibrous root systems enhance surface soil cohesion and resistance to wind erosion in degraded grasslands.

Root hairs, tiny structures extending from the root surface, significantly increase the root's ability to absorb water and nutrients. These hairs are particularly important in nutrient-poor or stressed environments, where efficient resource acquisition is essential for plant survival (Saleem et al., 2018). In addition, the branching pattern of roots, whether taprooted or fibrous, further affects the plant's ability to explore and penetrate the soil. Taproots, which are dominant, single roots, allow for deep soil exploration, while fibrous root systems, which spread extensively near the soil surface, facilitate rapid resource capture from upper soil layers (Viana et al., 2022). The spatial organization of roots within the soil profile, known as root zonation, reflects the functional specialization of different root regions. While shallow roots are often involved in rapid nutrient and water uptake, deeper roots play crucial roles in long-term water storage and nutrient acquisition during periods of stress (Karlova et al., 2021). Understanding root morphology and architecture provides insights into how grassland plants respond to different environmental conditions, influencing their ability to acquire and cycle resources within the ecosystem.

2.2. Root exudates and rhizosphere interactions

Root exudates are a diverse array of organic compounds secreted by plant roots into the surrounding soil, playing a pivotal role in shaping soil microbial communities and nutrient cycling dynamics in the rhizosphere, the soil zone directly influenced by root activity (Lv et al., 2023). These compounds include sugars, organic acids, amino acids, and phenolic compounds, which serve as energy sources for soil microbes and mediate critical plant-microbe interactions (Thies and Grossman, 2023).

The composition and quantity of root exudates vary according to plant species, environmental conditions, and nutrient availability (Iannucci et al., 2021). In this way, root exudates indirectly contribute to nutrient mobilization, improving the availability of essential elements for plant growth. Rhizosphere interactions go beyond nutrient acquisition (Francis et al., 2023). Beneficial microbes, such as nitrogen-fixing bacteria and phosphate-solubilizing fungi, can form symbiotic relationships with plant roots, increasing nutrient uptake efficiency and enhancing plant resistance to both biotic and abiotic stresses (Uyi et al., 2024). On the other hand, pathogenic microbes can also exploit root exudates to colonize plant roots, leading to root disease and reduced plant performance.

The exudation of organic compounds is particularly important in nutrient-poor soils, where plants rely on microbial partners to obtain

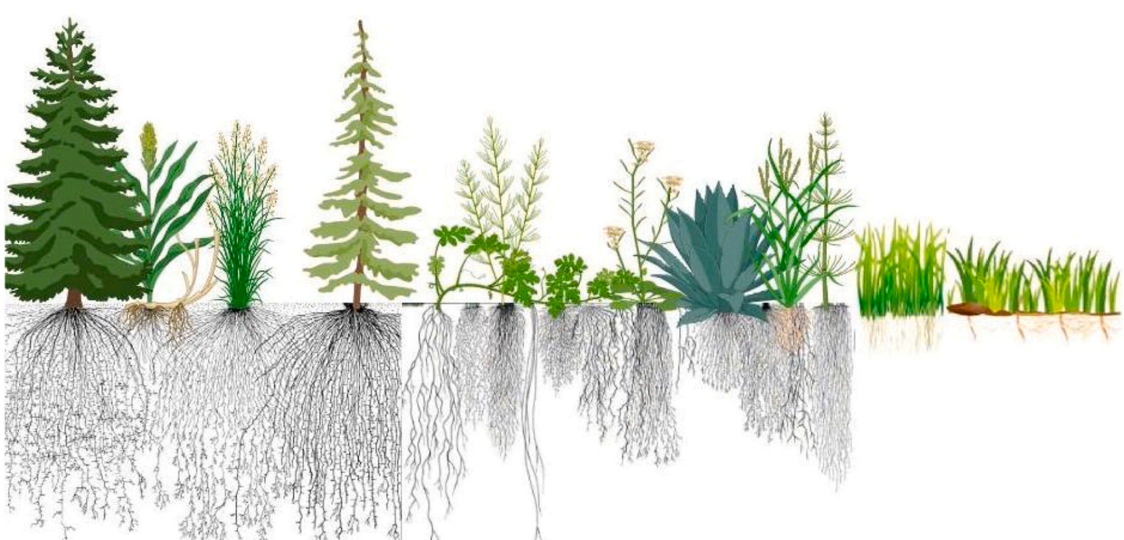

Fig. 2. Diversity of vegetation types and root structures in grassland ecosystems.

scarce nutrients (Uyi et al., 2024). By altering the composition of root exudates, plants can influence the microbial community structure in the rhizosphere, favouring microbes capable of releasing nutrients from organic or mineral sources (Yang et al., 2025). These rhizosphere interactions are fundamental to ecosystem productivity, as they regulate the availability of nutrients for plant uptake, especially in nutrient-limited environments (Yang et al., 2024).

2.3. Mycorrhizal associations

Mycorrhizal associations are symbiotic relationships between plant roots and specialized fungi, vital in nutrient acquisition and soil health. These fungi extend the plant's root system through a network of hyphae, which infiltrate the surrounding soil to access nutrients otherwise unavailable to plants (Eze et al., 2024). In grassland ecosystems, two primary types of mycorrhizal associations are common: arbuscular mycorrhizae (AM) and ectomycorrhizae (ECM).

Arbuscular mycorrhizae (AM) fungi form intimate associations with the roots of most grassland species. The fungal hyphae penetrate the plant's root cells, forming arbuscules, where nutrient exchange occurs (Kuyper and Jansa, 2023). In exchange for photosynthetically derived C, AM fungi provide plants with critical nutrients, particularly P and N. This mutualistic relationship enhances plant growth and resilience to environmental stress, particularly in nutrient-poor soils (Yang et al., 2023).

Ectomycorrhizae (ECM) are more commonly associated with trees and woody shrubs. In these associations, the fungal hyphae envelop the root surface without penetrating root cells, forming a sheath that facilitates nutrient exchange (Tanwir et al., 2023). Like AM fungi, ECM fungi improve nutrient uptake and increase plant resistance to environmental stresses such as drought and nutrient limitation.

Mycorrhizal networks can also link multiple plants, allowing for resource sharing between species. These "common mycorrhizal networks" enhance ecosystem stability by distributing nutrients and water among plants, promoting resilience to nutrient limitation and other environmental challenges (Ullah et al., 2024). Additionally, mycorrhizal associations contribute to C sequestration by promoting soil aggregation and increasing organic matter accumulation in soil.

2.4. Root turnover and decomposition

Root turnover is when roots die and are replaced by new growth, which drives C and nutrient cycling in grassland ecosystems. As roots die and decompose, they release stored C and nutrients into the soil, contributing to the formation of soil organic matter and the recycling of essential elements (Raza et al., 2023). The rate of root turnover varies among species and environmental conditions, with fine roots generally exhibiting faster turnover rates than coarse roots.

Root decomposition plays a critical role in nutrient cycling. As roots break down, microbes, including bacteria, fungi, and actinomycetes, decompose the organic compounds, releasing nutrients such as N, P, and K into the soil for plant uptake (Tariq et al., 2024). The decomposition rate is influenced by root chemical composition, soil moisture, temperature, and microbial community structure. Roots rich in lignin and complex carbohydrates decompose more slowly than those with more straightforward chemical compositions (Z. Yang et al., 2024). In addition to facilitating nutrient cycling, root decomposition contributes to the accumulation of SOC, critical in maintaining soil fertility, structure, and water retention. As root residues interact with mineral particles, they form soil aggregates, stabilizing C and enhancing the soil's capacity to support future plant growth (Attia et al., 2024; Francis et al., 2023).

Understanding the dynamics of root turnover and decomposition is essential for predicting how grassland ecosystems will respond to environmental changes such as climate variability, land use change, and nutrient availability. These processes directly influence soil health, ecosystem productivity, and the capacity of grasslands to sequester C in the long term (Paul, 2016).

3. Carbon and nutrient stocks in grassland ecosystems

Grassland ecosystems are globally significant reservoirs of C and nutrients, storing substantial amounts of organic matter in vegetation and soils. These stocks are crucial for ecosystem productivity, nutrient cycling, and the regulation of global biogeochemical cycles (Wang et al., 2021). The dynamic balance between C and nutrient inputs, storage, and outputs within these ecosystems underpins their ability to provide essential services such as soil fertility, biodiversity support, and climate regulation. Understanding the distribution, accumulation, and turnover of C and nutrient stocks in grassland ecosystems is vital for predicting ecosystem responses to environmental changes, such as shifts in land use and climate (Sanaei et al., 2018).

3.1. Aboveground and belowground carbon and nutrient stocks

Grassland ecosystems store C and nutrients in aboveground biomass (vegetation) and belowground compartments (roots, soil organic matter). Aboveground biomass comprises the living tissues of grasses, forbs, shrubs, and sometimes trees, which represent a critical reservoir of C and nutrients (Wang et al., 2021). The C stored in leaves, stems, and reproductive organs contributes directly to the terrestrial C pool, while the nutrients in these tissues play essential roles in ecosystem functioning and productivity (Sanaei et al., 2018).

The composition and productivity of aboveground vegetation are influenced by plant species diversity, climatic conditions, and land management practices (Dijkstra et al., 2021). The interconnections between C dynamics and nutrient cycling in grassland ecosystems emphasise the roles of plant species diversity, photosynthesis, and microbial activity in how plants sequester C while facilitating nutrient release through decomposition and interactions with beneficial and pathogenic microbes. Additionally, it highlights human-induced CO_2 emissions and their impact on these natural processes (Fig. 3). The turnover of aboveground biomass, through methods such as herbivory, plant senescence, and decomposition, continually recycles C and nutrients back into the ecosystem, supporting nutrient availability and soil organic matter formation (Panchal et al., 2022).

Belowground biomass, which includes living roots and associated rhizosphere organisms, is equally, if not more, important in determining the long-term storage of C and nutrients in grassland ecosystems (Dijkstra et al., 2021). Roots serve as a crucial interface between plants and the soil, facilitating nutrient uptake and water acquisition and playing a key role in stabilizing soil structure and preventing erosion. Root biomass also contributes to the accumulation of soil organic matter (SOM) through root exudation and the deposition of dead root tissues. SOC, the largest terrestrial C pool, originates from plant litter decomposition, root turnover, and microbial activity. Grassland soils, particularly in regions with high root biomass, can store significant amounts of SOC, especially in the upper layers where organic matter accumulates (Panchal et al., 2022). The stabilization of SOC is essential for maintaining soil fertility and ecosystem productivity, as it influences nutrient retention, water infiltration, and soil structure.

3.2. Nutrient cycling and stocks in grassland soils

Grassland soils are important reservoirs of essential nutrients such as N, P, K, Ca, magnesium (Mg), and sulfur (S). These nutrients support plant growth, soil microbial activity, and ecosystem productivity (Kang et al., 2023). Soil nutrient stocks vary depending on factors such as soil type, land use history, and environmental conditions, and they are tightly linked to decomposition, mineralization, and nutrient cycling processes.

The availability of nutrients in grassland ecosystems is driven by the decomposition of plant material (aboveground litter and root tissues),

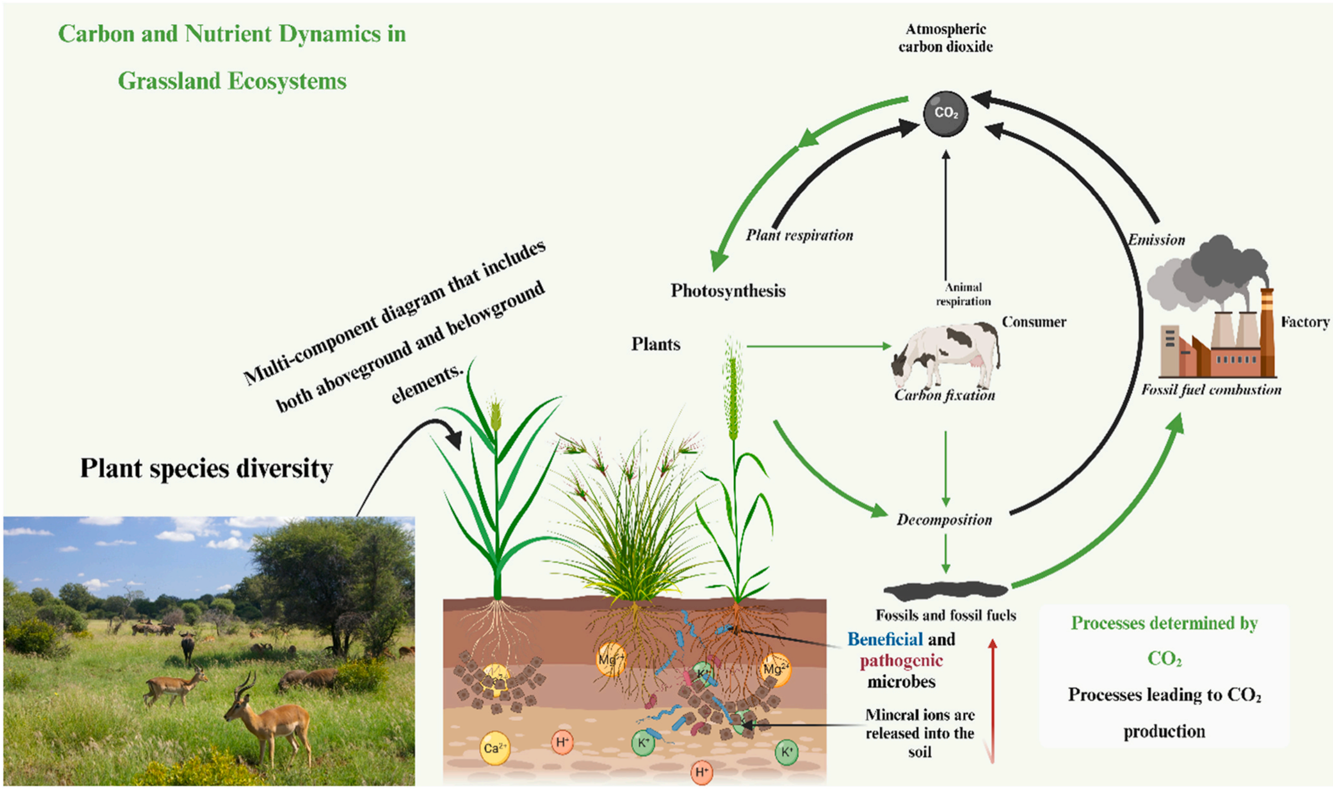

Fig. 3. The roles of plant species diversity, photosynthesis, microbial interactions, and anthropogenic CO_2 emissions in maintaining ecosystem health and productivity.

microbial activity, and interactions between plants and soil microorganisms. As plant litter decomposes, nutrients are gradually released into the soil, making them available for plant uptake. Nutrient availability is regulated by various processes, including mineralization (converting organic matter into inorganic forms), soil microbial activity, and nutrient leaching. In healthy grassland soils, these processes balance nutrient inputs and outputs, ensuring that plants have access to the nutrients needed for growth and development (Minnich et al., 2021). In addition to C, N is one of the most critical elements stored in grassland ecosystems. N is essential for protein synthesis, plant metabolism, and soil fertility, and it is often a limiting nutrient in terrestrial ecosystems. Grassland soils typically contain large amounts of organic nitrogen, which is gradually made available to plants through the activities of nitrogen-fixing bacteria and soil microbes. Similarly, P and K are critical nutrients that support plant growth, root development, and metabolic functions (Shi et al., 2025). Grassland soils rich in organic matter tend to have higher nutrient-holding capacities, supporting more incredible biodiversity and ecosystem resilience.

3.3. Litter, deadwood, and transient C pools

In grassland ecosystems, C and nutrients are stored in transient pools such as litter and deadwood. Though smaller than living biomass or soil organic matter, these pools play essential roles in ecosystem nutrient cycling and C sequestration. Litter includes dead plant material, such as leaves, stems, and reproductive structures, that falls to the ground and undergoes decomposition (Wang et al., 2025). As litter decomposes, it releases nutrients into the soil, contributing to nutrient availability for plants and soil organisms.

Deadwood, while more commonly associated with forest ecosystems, is also present in grassland systems, particularly in shrubland or savanna grasslands that contain woody species. Deadwood provides a habitat for a wide range of microorganisms, fungi, and invertebrates, which play crucial roles in the breakdown of organic matter and nutrient cycling (Minnich et al., 2021). The decomposition of deadwood and litter contributes to the formation of humus and stable organic matter, enhancing the nutrient-holding capacity of soils and supporting long-term soil fertility.

3.4. Impacts of land use and environmental changes on C and nutrient stocks

Land use changes, such as grazing, deforestation, cultivation, and urbanization, significantly influence grassland ecosystems' C and nutrient dynamics (Zhong et al., 2021). For instance, overgrazing can reduce plant biomass, disrupt root-soil interactions, and accelerate soil erosion, leading to the loss of C and nutrient stocks. Similarly, intensive agricultural practices, including plowing and monocropping, can deplete soil organic matter and reduce soil fertility, negatively impacting the ecosystem's capacity to sequester C and support biodiversity.

Conversely, land management practices such as reforestation, afforestation, and sustainable grazing can enhance C sequestration and nutrient cycling. By restoring vegetation cover and improving soil health, these practices help to build soil organic matter, enhance root biomass, and promote the accumulation of nutrients in soils. Environmental changes, including climate change, also affect C and nutrient stocks in grassland ecosystems. Changes in temperature, precipitation patterns, and CO_2 concentrations influence plant growth, litter decomposition rates, and soil microbial activity, all of which impact the balance of C and nutrient stocks (Wang and Kuzyakov, 2023). Grasslands in arid and semi-arid regions are particularly vulnerable to climate change, as altered precipitation regimes can exacerbate nutrient limitations and increase the risk of soil erosion and desertification.

3.5. The role of C and nutrient stocks in ecosystem services

The C and nutrient stocks in grassland ecosystems provide essential ecosystem services supporting natural biodiversity and human well-being. These services include soil fertility maintenance, water regulation, C sequestration, and providing habitat for various plant and animal species (Saleem et al., 2018). The ability of grasslands to store C and nutrients directly influences their capacity to mitigate climate change, maintain ecosystem resilience, and support sustainable agricultural practices. By quantifying C and nutrient stocks and understanding their spatial distribution, land managers and policymakers can develop more effective strategies for conserving grassland ecosystems and enhancing their resilience to environmental pressures (Freschet et al., 2021). Maintaining healthy C and nutrient stocks in grasslands is key to ensuring long-term ecosystem sustainability and mitigating the impacts of global environmental changes (Lal, 2018).

4. Effects of land use change on plant root mechanisms

Land use changes, such as grazing, cultivation, and deforestation, significantly influence plant root dynamics and their roles in C sequestration, nutrient cycling, and soil stability in grassland ecosystems (Pathan et al., 2020). Roots are highly responsive to external environmental pressures, with alterations in root morphology, biomass, and function directly affecting ecosystem processes. Understanding the impacts of land use on root systems is critical for managing grassland productivity, C storage, and overall ecosystem resilience (Liu et al., 2022). Figs. 4 and 5 illustrate how land management practices alter root mechanisms, with implications for ecosystem health.

Recent scientific evidence underscores that land use change is a powerful driver of belowground processes, primarily through its influence on root functional traits. For example, For instance, Ma et al., (2021) found that heavy grazing pressure in temperate grasslands reduced root biomass and fine root turnover, impairing nutrient retention and soil carbon inputs. Yang et al., (2024) reported that intensive tillage in semi-arid systems disrupted root system architecture, resulting in decreased infiltration and lower soil aggregate stability. In contrast, sustainable practices like crop rotation and cover cropping have been shown to promote deeper, denser root systems and enhance soil organic carbon (SOC) and nutrient retention (Attia et al., 2024; Recous et al., 2019). These findings highlight how land use strategies directly influence root morphology, architecture, and exudation patterns thereby shaping critical ecosystem services such as soil fertility, water regulation, carbon sequestration, and erosion control.

4.1. Grazing impacts on root biomass and distribution

Grazing is a predominant land-use practice in grassland ecosystems, with varying intensities that can benefit or harm root systems. The intensity and frequency of grazing influence root biomass, root distribution, and the overall health of grassland ecosystems (Ma et al., 2021). Overgrazing, as depicted in Fig. 4, can significantly reduce root biomass, particularly in the upper soil layers where most grass species concentrate their roots for nutrient and water uptake (Caldwell, 2021). This reduction in root biomass diminishes the capacity of the ecosystem to sequester C, cycle nutrients, and maintain soil structure. As grazing

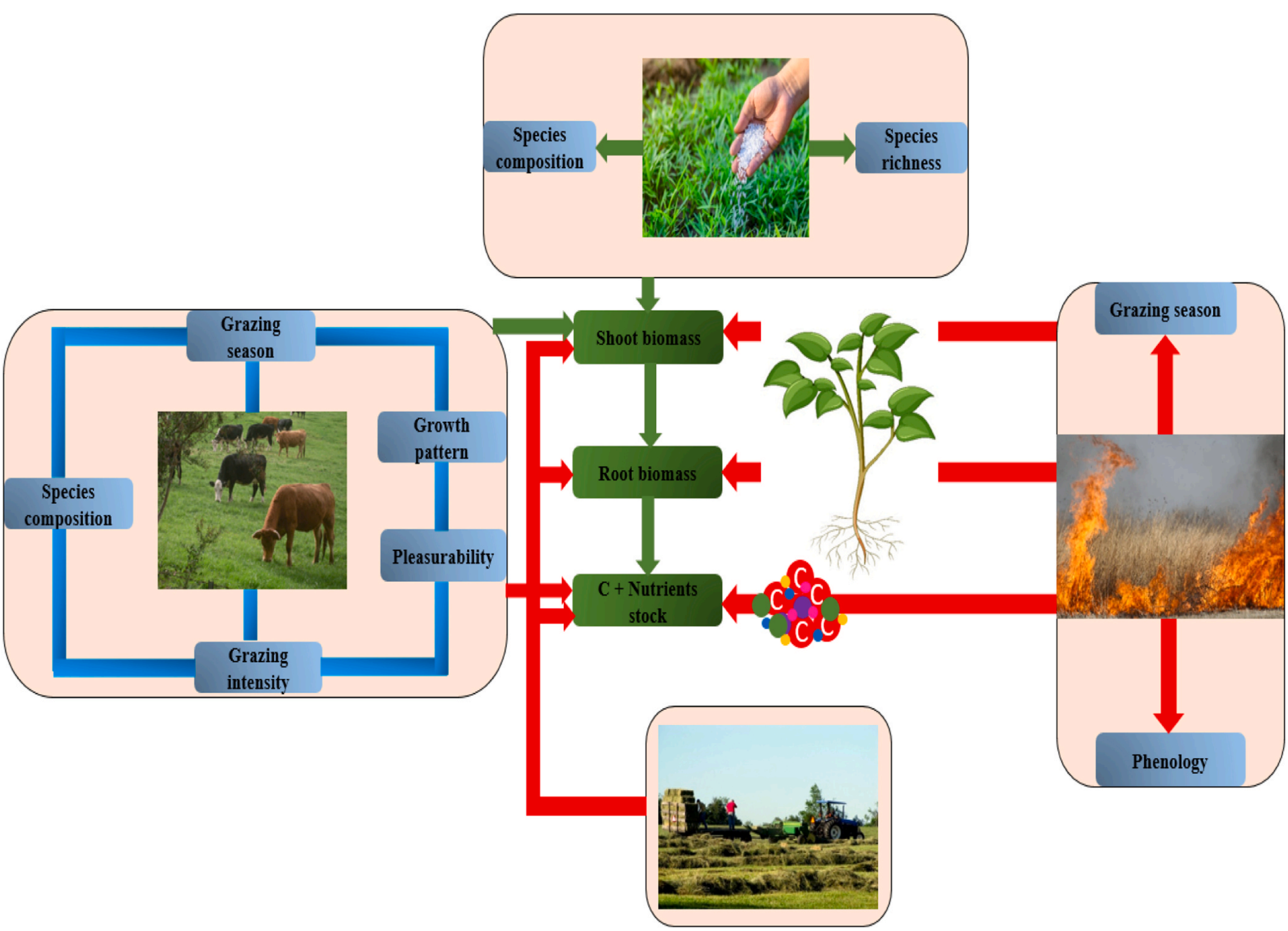

Fig. 4. The effects of land management practices on C and nutrient stocks in grassland plants.

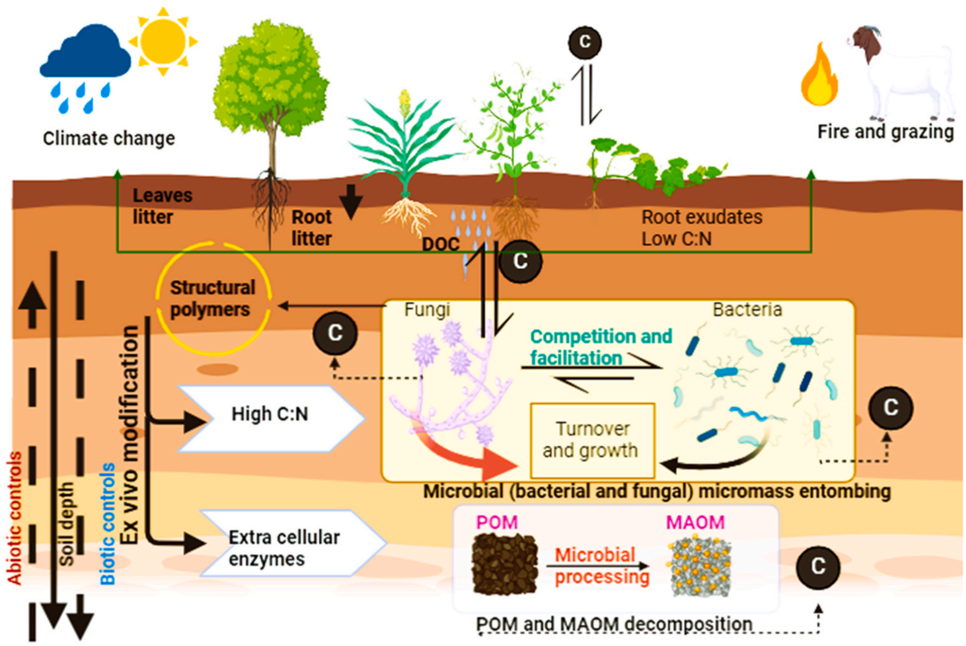

Fig. 5. Impact of Climate Change and Biotic Interactions on Soil C Dynamics.

animals remove aboveground biomass, the root-to-shoot ratio often declines, reducing the overall C input into the soil through root exudation and turnover.

Additionally, overgrazing compacts the soil due to trampling by livestock, which inhibits root penetration, reduces soil porosity, and limits water infiltration (Fig. 4). Soil compaction negatively impacts root growth by restricting access to essential resources such as oxygen and water, which in turn reduces root proliferation and biomass accumulation (Souther et al., 2019). This can further limit the ability of the ecosystem to sequester C and cycle nutrients effectively, as root systems are vital for facilitating these processes. However, moderate grazing can positively affect root dynamics by stimulating root turnover and improving soil organic matter cycling. As shown in Fig. 4, moderate grazing promotes root proliferation, particularly in species adapted to frequent grazing disturbances (Faghihinia et al., 2020). These plants may allocate more resources to root growth, increasing root depth and density in response to defoliation. This adaptation enhances the plants' ability to capture water and nutrients, which can help maintain ecosystem productivity and resilience (Caldwell, 2021). Furthermore, moderate grazing may encourage root turnover, which accelerates the deposition of organic matter into the soil, promoting C sequestration and nutrient cycling.

4.2. *Cultivation effects on root traits and functions*

Cultivation practices, particularly soil disturbance such as plowing and tillage, profoundly affect grassland root architecture and function. Fig. 4 illustrates how intensive tillage disrupts root systems, leading to reductions in root length, root branching, and the depth at which roots can grow. This alteration in root traits reduces the ability of plants to absorb water and nutrients from deeper soil layers, which can significantly impair ecosystem productivity and C storage (Wang et al., 2024). Shallow-rooted species dominate cultivated fields, limiting the depth at which C can be sequestered and stored in the soil. As a result, ecosystems subject to regular tillage often experience a decline in overall C stocks and nutrient cycling efficiency. The impacts of cultivation on root systems are particularly evident in soil compaction caused by the frequent use of heavy machinery during farming operations. Compaction decreases soil porosity, restricting the movement of air, water, and nutrients and ultimately hindering root penetration (Sha et al., 2024). This leads to stunted root growth and a reduction in the plant's ability to access deeper soil nutrients.

Consequently, cultivated soils may exhibit lower levels of root biomass and reduced nutrient uptake efficiency. In the long term, these effects can compromise the health of grassland ecosystems by depleting soil fertility and reducing the capacity for C sequestration (Wang and Kuzyakov, 2023).

Conversely, conservation tillage practices minimize soil disturbance and can significantly improve root health and enhance C sequestration. As highlighted in Fig. 4, conservation tillage allows for more extensive and deeper root systems, strengthening the plant's access to water and nutrients from lower soil horizons (Su et al., 2024). Conservation tillage fosters healthier root development and promotes soil C storage by reducing soil compaction and maintaining higher organic matter. Furthermore, these practices encourage the retention of crop residues on the soil surface, which provides additional organic material for soil microorganisms, enhances soil structure, and supports root growth (Wang and Kuzyakov, 2023).

In addition to improving root health, conservation tillage can enhance the interactions between plant roots and soil microorganisms, particularly mycorrhizal fungi. These symbiotic relationships are crucial for enhancing nutrient uptake, particularly in nutrient-poor soils (Ramesh et al., 2019). Mycorrhizal fungi extend the reach of plant roots, facilitating the uptake of P and other essential nutrients that would otherwise be inaccessible to the plant. As Fig. 4 shows, conservation tillage encourages the development of these root-microbe interactions, contributing to improved nutrient cycling and soil health.

5. Influence of climate change on plant root responses

Climate change profoundly affects plant root systems, altering their growth patterns, distribution, and interactions with soil processes. Root systems are vital in mediating how plants respond to environmental stressors such as temperature fluctuations, changes in precipitation patterns, and increasing atmospheric CO_2 levels (Kumawat et al., 2022). Understanding these responses is crucial for predicting ecosystem resilience and developing management strategies to maintain ecosystem services in grasslands. Fig. 5 illustrates how climate variables such as temperature and precipitation influence root dynamics, affecting C sequestration and nutrient cycling (Etesami and Beattie, 2017).

Climate change through rising temperatures, altered precipitation regimes, and increased frequency of extreme events profoundly affects root morphology, exudation, and biomass allocation, thereby influencing carbon and nutrient dynamics in grassland soils. Recent experimental studies have shown that warming can shift root biomass allocation to deeper soil layers, altering the distribution and stabilization of carbon inputs (Sharma et al., 2025). Moreover, drought conditions often reduce root exudation rates and microbial activity, suppressing nutrient mineralization and slowing down soil nitrogen cycling (Parasar et al., 2024; L. Zhang et al., 2025). In alpine and semi-arid grasslands, shifts in rainfall patterns have been linked to reduce fine root turnover and changes in mycorrhizal colonization, limiting the capacity for carbon sequestration and phosphorus uptake (Miao et al., 2025; J. Wang et al., 2024). These climate-driven modifications to root functions directly affect the resilience and nutrient balance of grassland ecosystems, underscoring the importance of root dynamics in predicting ecosystem responses to global change.

5.1. Temperature effects on root growth and activity

Temperature is a critical factor influencing root growth, elongation, and nutrient uptake. Temperature increases and decreases directly affect root system architecture, C allocation to roots, and interactions with soil microorganisms (Dolezal et al., 2021). In warmer climates, as shown in Fig. 5, elevated temperatures can promote microbial activity and nutrient cycling, increasing nutrient availability to plants in the short term. However, prolonged exposure to high temperatures can hinder root development and disrupt normal plant functioning (Calleja-Cabrera et al., 2020). Root elongation slows down significantly under extreme heat, limiting the plant's ability to absorb water and nutrients effectively. Furthermore, high temperatures often result in more excellent evaporation rates, reducing soil moisture availability and compounding the stresses faced by roots (Fonseca de Lima et al., 2021).

As the climate warms, root biomass may shift more profoundly into the soil profile, where moisture and cooler temperatures are more stable. This shift can alter C allocation to roots, with plants investing more in deeper roots to access water and nutrients from lower soil horizons (Fonseca de Lima et al., 2021). While deeper root systems can improve plant resilience to drought and high temperatures, they may reduce nutrient uptake efficiency from the upper soil layers, where most soil nutrients are concentrated. This trade-off between deeper root systems for water acquisition and shallower roots for nutrient absorption is a key area of interest in understanding plant responses to warming climates.

Moreover, temperature fluctuations can affect root metabolic activity, particularly regarding nutrient uptake efficiency. Warmer temperatures generally increase the metabolic rates of roots, enhancing their ability to acquire nutrients, but these benefits are negated when temperatures exceed the optimal range for root function (Dolezal et al., 2021). Under extreme heat, root respiration increases, which can deplete carbohydrate reserves in the plant, limiting the energy available for root growth and maintenance. Consequently, root systems may become more vulnerable to environmental stressors, reducing ecosystem productivity and lowering C sequestration potential. As climate change progresses, the impact of temperature variability on root systems will become increasingly significant (Beedlow et al., 2013). A comprehensive understanding of how plants adapt their root systems to fluctuating temperatures will be essential for developing strategies to maintain plant health and ecosystem services in the face of warming global temperatures (Lv et al., 2023).

5.2. Precipitation patterns and root water uptake strategies

Precipitation patterns are another crucial climate variable that influences root water uptake strategies, particularly in regions experiencing increased drought or shifts in seasonal rainfall distribution (Zhao et al., 2024). Precipitation frequency and intensity changes directly impact soil moisture availability, affecting root growth, distribution, and water uptake efficiency. As illustrated in Fig. 5, plants respond to water-limited conditions by developing more profound and more extensive root systems that can access moisture from lower soil layers (Wang et al., 2023). This adaptation is critical for maintaining ecosystem productivity during drought, especially in grassland ecosystems prone to seasonal water shortages.

In response to prolonged dry conditions, plants often prioritize the growth of deeper roots over shallower roots to tap into groundwater reserves or soil moisture stored in deeper horizons. This shift in root architecture allows plants to maintain water uptake when surface soil layers dry (Gholizadeh et al., 2024). Plants in arid environments or regions with erratic precipitation patterns may also exhibit increased root length density and root branching, which enhances their ability to explore a larger volume of soil for water. These adaptations improve drought tolerance but can also reduce nutrient uptake from the nutrient-rich upper soil layers (Yasin et al., 2024).

On the other hand, in regions where precipitation patterns become more variable with alternating periods of heavy rainfall and drought, plants must adjust their root growth to optimize water capture during wet periods while maintaining access to deeper soil moisture during dry spells (Duchesneau et al., 2024). As shown in Fig. 5, shallow-rooted species are better equipped to capture rainfall immediately after a precipitation event but are more vulnerable to drought conditions. Conversely, deep-rooted species can sustain water uptake over prolonged dry periods but may be less efficient at capturing water from sudden surface rainfall events (Zhou et al., 2024).

Changes in precipitation also affect root-microbe interactions in the rhizosphere. In water-limited environments, roots often form symbiotic relationships with mycorrhizal fungi, which enhance water uptake and nutrient acquisition (Gupta et al., 2020). These relationships become even more critical under drought conditions, as mycorrhizal networks extend beyond the root zone to access water and nutrients from distant soil areas. Conversely, excessive precipitation or flooding can disrupt these interactions by creating anaerobic conditions in the soil, reducing microbial activity and negatively affecting root function (Molvar et al., 2024).

As climate change intensifies, shifts in precipitation patterns will likely lead to changes in plant species composition and root water uptake strategies. Species with more remarkable root plasticity, those that can modify their root architecture in response to soil moisture availability, will be better positioned to survive in fluctuating climates (Zhao et al., 2024). Understanding these adaptive root strategies will be key to managing ecosystems for improved resilience to water stress and maintaining ecosystem services such as C sequestration and nutrient cycling (Xing et al., 2024).

5.3. Elevated CO_2 levels and root C allocation

Elevated CO_2 levels significantly impact plant root C allocation, influencing root growth, morphology, and function. As CO_2 concentrations rise, plants allocate more biomass to their root systems, increasing root elongation, branching, and overall biomass accumulation (Honeker et al., 2023; Raza et al., 2023). This enhanced root biomass allocation improves the plant's ability to acquire resources from deeper soil layers, thereby boosting productivity and promoting ecosystem C sequestration. Elevated CO_2 often triggers the development of more profound and extensive root systems, enabling plants to access water and nutrients more efficiently (Zhou et al., 2024).

Additionally, higher CO_2 levels encourage the proliferation of fine roots, increasing the surface area for nutrient uptake and enhancing C storage in root tissues. The morphology of roots changes, enabling plants to optimize the acquisition of below-ground resources (Honeker et al., 2023). Moreover, CO_2 enrichment alters rhizosphere interactions by stimulating root exudation plants to release more sugars, amino acids, and organic acids into the soil. These exudates promote microbial activity, enhancing nutrient cycling and soil organic matter turnover, contributing to further C storage in the rhizosphere and microbial biomass (Fig. 5).

Elevated CO_2 also shifts how C is allocated among root components. Plants may prioritize C allocation to structural roots for stability, absorptive roots for nutrient uptake, or storage roots for long-term carbohydrate storage (Hodge and Storer, 2015). These shifts help optimize resource acquisition and support ecosystem resilience under changing environmental conditions. The increased root turnover and exudation from elevated CO_2 enhance soil organic matter accumulation and soil C sequestration (Honeker et al., 2023). Recent studies confirm that root-derived C contributes more stably and substantially to long-term SOC pools than shoot-derived inputs. For instance, Hupperts et al., (2025) demonstrated that fine roots and mycorrhizal hyphae contribute disproportionately to persistent SOC due to slower decomposition rates and intimate soil–mineral interactions. Similarly, Sandhu et al., (2025) used modeling approaches to show that systems with extensive root biomass (e.g., perennial rotations and cover cropping) significantly increased modeled SOC stocks in temperate agroecosystems. In nitrogen-deficient environments, increasing C allocation to roots and mycorrhizal fungi under elevated CO_2 can stimulate microbial N-ineralization, promoting nutrient cycling and boosting ecosystem productivity (Hodge and Storer, 2015). Understanding how plants allocate C to their root systems under elevated CO_2 is crucial for developing sustainable land management strategies and enhancing C sequestration in a changing climate (Hartmann et al., 2020).

6. Implications for C and nutrient dynamics in grassland ecosystems

Grassland ecosystems play a crucial role in global C sequestration and nutrient cycling, and the stability of these processes is highly sensitive to environmental disturbances (Xing et al., 2024). Extreme weather events, such as droughts, floods, and heatwaves, profoundly affect plant growth, root development, and soil organic matter dynamics, significantly disrupting C and nutrient cycling (Liu et al., 2023). These disturbances can temporarily reduce the ability of grassland ecosystems to sequester C and recycle nutrients, with cascading effects on ecosystem productivity and resilience (Honeker et al., 2023; Raza et al., 2023).

6.1. Disruptions in carbon sequestration

Droughts, in particular, severely limit the capacity of grasslands to sequester C. Reduced soil moisture levels inhibit root growth and decrease the availability of nutrients, thereby limiting photosynthesis and C allocation to belowground biomass (Hartmann et al., 2020). The drying of soils also impairs microbial activity, leading to slower rates of organic matter decomposition and nutrient mineralization. As a result, drought conditions can lead to reduced C inputs to the soil through litterfall and root exudation, ultimately reducing SOC stocks.

Flooding events, on the other hand, can lead to soil anoxia (oxygen deficiency) and the loss of root biomass due to waterlogging, disrupting the normal functioning of roots and reducing their ability to absorb nutrients. Prolonged waterlogged conditions can also stimulate microbial processes that promote the decomposition of organic matter, resulting in increased C emissions through soil respiration (Hodge and Storer, 2015). However, flooding can also temporarily increase the availability of specific nutrients by mobilizing organic matter and sediments, potentially enhancing plant growth in floodplain areas once the water recedes. As illustrated in Fig. 5, these extreme events often lead to short-term reductions in C sequestration, but recovery periods following these disturbances can also offer opportunities for enhanced C input. Following droughts or floods, regrowth of vegetation and increased root activity can boost soil C accumulation. This recovery is supported by the ability of plants to adapt their root systems, either by growing deeper roots to access moisture during drought or by rapidly regenerating shallow roots after flooding. These adaptive responses help mitigate long-term ecosystem degradation and allow for the eventual restoration of C sequestration rates (Liu et al., 2023).

6.2. Impact on nutrient cycling

Extreme weather events can also disrupt nutrient cycling processes in grassland ecosystems. Drought conditions reduce soil microbial activity and slow N-fixation rates, mineralization, and other key nutrient cycling processes (Srivastav et al., 2021). With less microbial decomposition of organic matter, the release of essential nutrients like nitrogen, P, and K is delayed, negatively affecting plant growth and ecosystem productivity. In water-limited environments, plants may experience nutrient deficiencies that further exacerbate the effects of drought on ecosystem functioning (Kumar et al., 2022). Flooding, in contrast, can lead to nutrient leaching, where excessive water runoff carries away nutrients from the soil, particularly N and P. This loss of nutrients reduces the fertility of grassland soils and can lead to eutrophication in downstream water bodies. However, in certain flood-prone regions, nutrient-rich sediments deposited by floodwaters can replenish soils, restoring some of the lost nutrients and supporting post-flood plant growth (Das et al., 2022). As shown in Fig. 5, these nutrient cycling dynamics are closely tied to changes in soil moisture and microbial activity, which are influenced by extreme weather conditions.

Roots facilitate nutrient cycling via rhizodeposition, exudate release, and interactions with rhizosphere microbes. Root exudates stimulate microbial enzyme production, accelerating N mineralization and P-solubilization. According to Lv et al., (2023), root exudation in diverse grasslands increased microbial C-use efficiency and nutrient turnover. Kuyper and Jansa, (2023) emphasized that mycorrhizal–root associations boost nutrient uptake and mediate efficient belowground nutrient cycling, especially in P-limited soils.

6.3. Ecosystem recovery and resilience

The ability of grassland ecosystems to recover from extreme weather events depends mainly on plant roots' resilience and capacity to adapt to changing conditions. Drought-tolerant species, for example, often develop deeper root systems that allow them to access water from lower soil layers during dry periods (Iqbal et al., 2020). In contrast, flood-tolerant species may have shallow root systems with adaptations like aerenchyma tissues that facilitate gas exchange in waterlogged soils. These adaptive strategies are critical for maintaining ecosystem functions due to climate variability (Sanders and Markhart, 2023).

Plant roots play a pivotal role in restoring ecosystem productivity during recovery. The regrowth of root systems helps to stabilize soils, improve water infiltration, and enhance nutrient uptake. Additionally, the recovery of microbial communities in the rhizosphere supports the resumption of nutrient-cycling processes, facilitating the restoration of soil fertility and plant growth (Upadhyay, 2020). As plants recover and re-establish their root systems, they contribute to rebuilding SOC stocks, ultimately helping grassland ecosystems regain their C sequestration capacity. Post-disturbance recovery processes sustain long-term ecosystem resilience (Fig. 5). While extreme weather events may cause temporary reductions in C and nutrient cycling, the ability of grassland ecosystems to bounce back depends on the adaptive capacity of plant roots and the ecosystem's underlying biological processes (Yanagi, 2024).

6.4. Long-term implications for ecosystem services

The cumulative effects of repeated extreme weather events, particularly in climate change, could lead to more lasting disruptions in C and nutrient dynamics (Minnich et al., 2021). If grassland ecosystems experience prolonged periods of drought or recurrent flooding, the recovery of root systems and the restoration of C sequestration and nutrient cycling may be delayed or incomplete. This could reduce ecosystem services, such as decreased soil fertility, lower biodiversity, and diminished C sequestration potential (Ma et al., 2021).

In the long term, managing grassland ecosystems to enhance root-driven processes such as improving soil organic matter, promoting plant biodiversity, and adopting sustainable land-use practices will be critical for maintaining their resilience to climate change (Caldwell, 2021). By supporting the natural recovery processes of plant roots and their associated microbial communities, land managers can help ensure that grasslands continue to provide essential ecosystem services, even in the face of increasing environmental stressors.

7. Management strategies for sustaining root-driven ecosystem services

Adaptive and sustainable management strategies are essential to sustain the vital ecosystem services driven by plant roots in grassland ecosystems. These strategies should improve soil health, foster biodiversity, and promote ecosystem resilience in changing environmental conditions. The vitality and functionality of root systems play a crucial role in the capacity of grasslands to sequester carbon, cycle nutrients, and maintain ecological stability.

To support a clearer understanding of these linkages, Fig. 6 provides a conceptual framework that illustrates how grassland management practices such as conservation tillage, perennial planting, and cover cropping affect root traits and associated belowground processes, ultimately influencing ecosystem outcomes like soil carbon storage, nutrient availability, and structural stability.

7.1. Enhancing root functionality through perennial species

One of the most effective strategies for sustaining root-driven ecosystem services is the restoration and management of perennial plant species with deep, extensive root systems. How these deep-rooted species improve critical soil properties, such as soil structure, water retention, and nutrient cycling (Fig. 7). Deep-rooted plants stabilize soils and enhance water infiltration into deeper soil layers, reducing the risk of soil erosion and improving the soil's ability to retain moisture during periods of drought (Villalobos-Soublett et al., 2022). This, in turn, supports long-term ecosystem productivity by ensuring that plants can access water and nutrients during dry conditions (Kang et al., 2021).

Restoring perennial species also contributes to C sequestration. The extensive root systems of perennials store a significant amount of C below ground, helping to build soil organic matter and enhance soil fertility. By promoting the use of perennial grasses, shrubs, and trees in grassland management, land managers can improve the overall resilience of ecosystems to climatic and anthropogenic disturbances (Zahoor et al., 2019).

7.2. Implementing sustainable land management practices

Land management practices must focus on maintaining healthy soils and promoting diverse plant communities to maximize the ecosystem benefits of root systems. Several sustainable management techniques have been proven to enhance root-driven ecosystem services, including:

Conservation Tillage: Conservation tillage minimizes soil disturbance, which helps protect root structures and preserve soil organic matter. Roots can grow more extensively by reducing the frequency and intensity of tillage, facilitating nutrient uptake and C sequestration. Additionally, conservation tillage reduces erosion and improves water infiltration, leading to healthier, more productive soils (Hornstein and Sederoff, 2024).

Agroforestry: Integrating trees and shrubs into grassland ecosystems through agroforestry practices enhances root diversity and deepens the soil profile's capacity to store C. The roots of trees in agroforestry systems stabilize soil, increase water retention, and create habitat for diverse soil microbial communities. These systems also improve nutrient cycling by enhancing the transfer of nutrients from deeper soil layers to surface plants (Mohanty et al., 2024).

Crop Rotation and Cover Cropping: Rotating crops and using cover crops help maintain soil fertility and prevent nutrient depletion. Diverse crop rotations ensure that different root systems are present in the soil, which can help break pest cycles, reduce soil compaction, and enhance soil organic matter accumulation (Attia et al., 2024). Cover crops, in particular, protect soil from erosion, improve water retention, and increase the availability of nutrients to subsequent crops through root-driven nutrient cycling processes (Villalobos-Soublett et al., 2022).

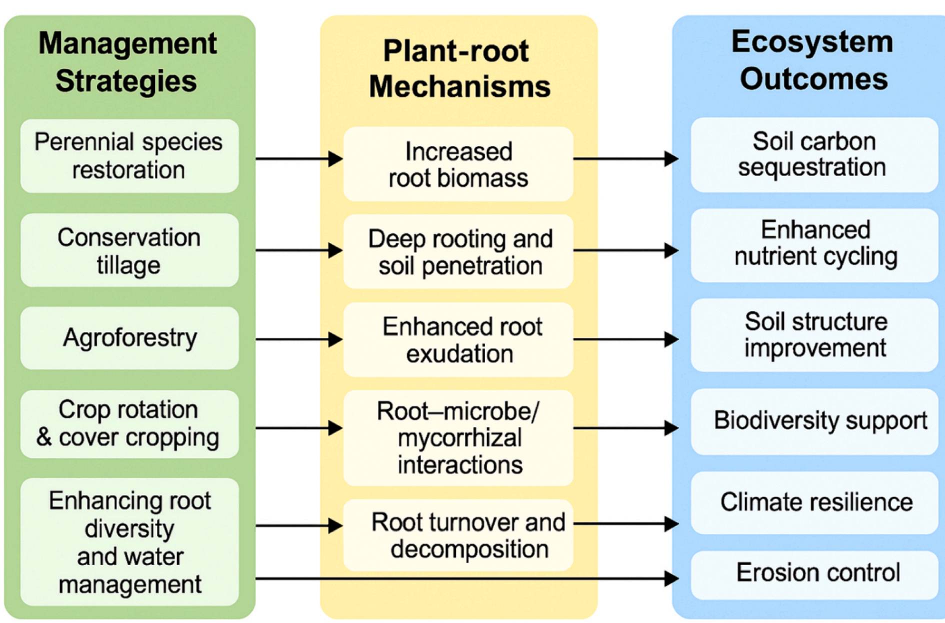

Fig. 6. Conceptual framework illustrating how various grassland management strategies influence root traits and processes (e.g., root biomass, depth, exudation, and root–microbe interactions), which in turn affect key ecosystem outcomes such as soil carbon sequestration, nutrient cycling, soil health, biodiversity, and climate resilience.

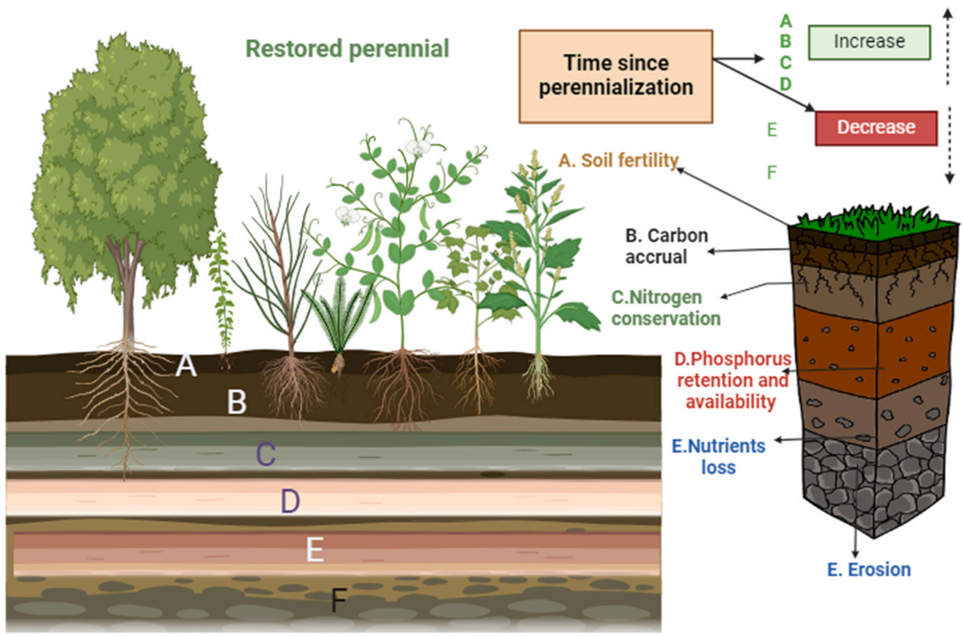

Fig. 7. Restored Perennial Stages Over Time. A. Soil Fertility: Refers to the ability of soil to sustain plant growth and is indicated by the health of perennial plants. B. C Accrual: Represents C accumulation in the soil, enhancing soil structure and fertility. C. N-Conservation: The process by which N is retained in the soil, crucial for plant growth. D. P-Retention and Availability: Indicates the soil's capacity to retain P, which is essential for plant development. E. Nutrient Loss: Refers to the depletion of soil nutrients over time due to various factors such as leaching. F. Erosion: The gradual wearing away of soil can lead to nutrient loss and reduced soil fertility.

7.3. Promoting biodiversity and root diversity

Root-driven ecosystem services are directly tied to plant biodiversity. Diverse plant communities with varying root morphologies and depths create a more resilient and sustainable ecosystem. Each plant species contributes unique benefits to soil health and nutrient cycling, with some species improving N-fixation, others enhancing water infiltration, and some contributing to C sequestration. Fig. 7 shows how increasing root diversity supports overall ecosystem resilience, especially in environmental stressors like drought and extreme weather.

Incorporating nitrogen-fixing legumes, deep-rooted perennials, and drought-tolerant plants into grassland management promotes niche complementarity, where plants occupy various soil layers and access different resources (Pathak et al., 2024). This reduces competition for nutrients and water, ensuring that resources are utilized efficiently. A more diverse plant community is better equipped to recover from disturbances, such as overgrazing or climate extremes, as it can regenerate root systems more rapidly and maintain ecosystem functions (Ding et al., 2024).

7.4. Adaptive water and nutrient management

Sustaining root-driven services requires careful water and nutrient management practices that support optimal root growth and soil health. Implementing precision irrigation techniques, such as drip irrigation or soil moisture sensors, ensures that plants receive adequate water without causing soil erosion or waterlogging. These practices promote efficient water use, particularly in regions with limited water availability, and support the growth of robust root systems capable of accessing deep water reserves (Hornstein and Sederoff, 2024).

Similarly, nutrient management must balance organic and inorganic inputs to support root-driven nutrient cycling. Integrating organic fertilizers, compost, and crop residues into soil management increases soil organic matter content, improves soil structure, and enhances root health. Avoiding excessive chemical fertilizers helps prevent nutrient imbalances that can harm root systems and lead to nutrient runoff. A balanced approach ensures roots can access the necessary nutrients to support plant growth while minimizing environmental degradation (De Mandal et al., 2021).

7.5. Monitoring and adapting to changing conditions

Continuous monitoring of soil health, root dynamics, and ecosystem responses is essential to ensure the long-term sustainability of root-driven ecosystem services. Technologies such as remote sensing, soil sensors, and root imaging tools provide valuable insights into how root systems interact with their environment. Regular monitoring allows land managers to assess the effectiveness of management practices and make necessary adjustments in response to changing environmental conditions, such as shifts in precipitation patterns or increased temperatures (Kisekka et al., 2022). Adaptive management strategies involve engaging local stakeholders and using participatory research to ensure land management practices respond to ecological and community needs. By promoting collaborative approaches and integrating scientific research with practical knowledge, adaptive management fosters the resilience of grassland ecosystems and the sustainability of root-driven services (Altieri et al., 2015).

8. Future directions, research needs, and conclusion

Advancements in technology offer exciting opportunities for studying plant roots in grassland ecosystems. Tools like rhizotrons and minirhizotron imaging provide non-invasive insights into root dynamics, while high-tech platforms like X-ray CT and 3D laser scanning allow detailed analysis of root traits. Additionally, technologies such as ground-penetrating radar and molecular tools like DNA barcoding enhance our understanding of root-soil interactions and root responses to environmental stress. These advancements help researchers explore root roles in nutrient cycling, C sequestration, and water management. However, knowledge gaps remain. Despite technological progress, root responses to environmental changes, such as belowground interactions with soil microorganisms, are underexplored. Longitudinal studies are needed to capture root system adaptation over time, and fine-scale root dynamics require more accurate measurement techniques. Moreover, understanding root plasticity and resilience under future climate scenarios is crucial for predicting ecosystem responses to global changes. Addressing these gaps will require interdisciplinary collaboration across ecology, genetics, and soil science to develop comprehensive insights into root responses and their broader ecosystem impacts.

Interdisciplinary approaches are key to advancing root ecology research. Roots interact with various elements such as soil, water, nutrients, microbes, and other plants across multiple scales. Researchers can better understand root function in ecosystem dynamics and resilience by integrating knowledge from hydrology, microbiology, and ecosystem ecology. Collaboration fosters methodological innovation and reveals complex feedback loops and emergent properties in root-soil systems, helping address real-world challenges such as soil degradation and climate change.

In conclusion, root ecology is essential for understanding ecosystem sustainability. Technological advances have opened new avenues for studying roots' complex interactions with their environment. At the same time, interdisciplinary research has uncovered roots' critical role in nutrient cycling, C sequestration, and ecosystem resilience. As we face global environmental challenges, root ecology provides valuable insights into maintaining ecosystem health and resilience. Through continued exploration, we can develop sustainable land management practices and better understand the future of ecosystems.

Author contributions

AW, XQ, MM, and XY conceptualized and designed the manuscript. The manuscript was written and revised by AW, HX, and AA, reviewed and gathered the literature. AW, YY, and AW organized and structured the information. All authors reviewed and contributed to the text of the manuscript.

CRediT authorship contribution statement

Abdul Waheed: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Xu Qiao:** Visualization, Software, Data curation. **Murad Muhammad:** Validation, Software, Data curation. **Yeernazhaer Yiremaikebayi:** Validation, Software, Resources. **Xie Yingying:** Validation, Software, Data curation. **Hailiang Xu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Aili Aishajang:** Writing – review & editing, Supervision, Funding acquisition. **Abdul Wahab:** Software, Formal analysis, Data curation.

Informed consent statement

Not applicable.

Institutional review board statement

Not applicable.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109865.

Data availability

No data was used for the research described in the article. Data sharing not applicable – no new data generated, or the article describes entirely theoretical research

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