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# Perennial grasses: natural allies for soil health and biodiversity, climate change mitigation, and invasive plant management

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## Abstract

Climate change and invasive alien plant species (IAPs) pose environmental challenges that affect soil health, biodiversity, and sustainability. This review investigates the potential of perennial grasses as a sustainable eco-friendly alternative solution for promoting soil health and biodiversity, mitigating climate change, and combating IAPs. An extensive review of global research and applications of perennial grasses was conducted, and the benefits of perennial grasses in reducing climate change and IAP impact are highlighted in this review paper. Overall, perennial grasses can help mitigate climate change and combat IAPs. Their dense and extensive root system, drought-resistant, and water-efficiency make them effective at sequestering, and storing carbon, mitigating greenhouse gas emissions, and adapting to climate fluctuations. They also reduce the need for tillage and synthetic fertilizers, enhancing ecosystem resilience to climate change. This suggests that incorporating perennial grasses into land management can help with climate change mitigation and adaptation, resulting in more sustainable and resilient ecosystems. Besides, well-managed perennial grasses can considerably reduce IAPs' impact of due to their suppressive ability, enhanced by strong root systems and competitive growth patterns. Moreover, perennial grasses offer a sustainable and long-term solution to the challenges posed by IAPs owing to their capacity to restore and maintain native plants and promote soil biodiversity, ecosystem health, and resilience following restoration. Thus, integrating perennial grasses into restoration and management strategies can allow land managers and ecologists to effectively combat IAPs. Overall, this review advocates for the inclusion of perennial grasses in conservation and restoration initiatives.

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## Introduction

Perennial grasses [e.g., switchgrass (*Panicum virgatum*), big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*), little bluestem (*Schizachyrium scoparium*), Maasai love grass (*Eragrostis superba*), and bush ryegrass (*Enteropogon macrostachyus*)] are plant species that live for more than two years with deep root systems and the capacity to grow in a variety of climates[1−5]. Although often overlooked, perennial grasses serve an important role in ecosystems, particularly in maintaining soil health and biodiversity, climate change mitigation, and combating alien invasive plants (AIPs)[1,4]. Thus, they are simply natural allies for soil biodiversity conservation, invasive plant management, and climate change mitigation[6,7]. The deep root systems of perennial grasses help soil structure by improving aeration, increasing water infiltration, and lowering soil erosion[1,5]. Also, their extensive root network supports the stability of the soil, making it less susceptible to degradation and encouraging a healthier ecology overall[1,8]. Further, they play a key role in the nutrient cycle by maximizing nutrient utilization and minimizing leaching[9,10]. In addition, perennial grasses contribute organic matter to the soil through biomass, which decomposes over time and enriches the soil with critical nutrients[11−13]. This process improves soil fertility, increasing productivity for other plant species, and agricultural activities[9,12].

IAPs, also known as non–native or exotic species, are plants introduced to an ecosystem where they do not naturally occur[14−16] and pose a severe ecological, economic, and social impacts[17,18]. Unlike native species, IAPs often lack natural enemies and diseases in their new environments, allowing them to proliferate unrestrictedly[19,20]. Their invasions lead to the displacement of native flora as they outcompete native species for resources i.e., light, water, and nutrients[21,22]. As a result, causing a reduction in biodiversity and the alteration of ecosystem functions, often forming dense monocultures that hinder the growth of other plants and disrupt habitats for native wildlife[23,24]. Moreover, IAPs can alter soil chemistry and hydrology thereby negatively impacting soil biodiversity[6,7,15,25]. IAPs can further impact human health by increasing allergens and providing a habitat for disease vectors[15]. Efforts to manage IAPs typically involve early detection, prevention, and rapid response, such as biological control, mechanical removal, and herbicide treatment[19,25,26]. Although the role of perennial grasses in combating IAPs has been seldom investigated, available studies show that effective management requires integrated eco-friendly management incorporating competitive native perennial grasses to suppress IAPs[6,8,15,27].

Furthermore, perennial grasses are ecologically significant because they enhance species diversity and soil biodiversity i.e., living forms found in soil, which includes microorganisms (bacteria and fungi), mesofauna (nematodes and mites), and macrofauna, i.e., earthworms and insects[28−32]. This diversity is critical to ecosystem function and plays an important role in nutrient cycling, soil structure maintenance, and plant growth promotion[29,30]. They contribute to nutrient-cycling activities by breaking down organic materials into simpler compounds that perennial grasses and other plants can consume, decomposing dead plants and animals, and releasing nutrients back into the soil, thus increasing soil fertility[32−34]. Further, perennial grasses also promote plant-soil symbiotic relationships such as mycorrhizal associations and rhizobium symbioses, which improves soil health and plant growth[29]. These benefits are enhanced by perennial grasses' root exudates, which support both soil microbial diversity and activity, resulting in a more dynamic and resilient soil environment[1]. However, extreme weather events, such as floods and droughts, as well as IAPs can cause soil organism loss and structural damage, thereby impeding the roles of soil organisms[35−37]. Further, increased temperatures can disrupt microbial activity and nitrogen cycling mechanisms, impacting soil health, and productivity[37,38]. Addressing these challenges needs long-term integrated management approaches that maintain natural ecosystems and increase soil biodiversity, as well as IAP control and climate change mitigation. For instance, promoting the use and maintaining the diversity of perennial grasses in rangelands and agricultural habitats[1,39,40].

Climate change which is the average change in the earth's temperature and precipitation patterns can also disrupt the delicate balance of soil biodiversity[37,41]. It is driven primarily by human activities i.e., burning fossil fuels, deforestation, and industrial processes which lead to an unprecedented rise in greenhouse gases, such as carbon dioxide and methane in the atmosphere[37,42]. Often the earth's surface temperature increases concomitantly with these greenhouse gasses[41]. Increased temperatures contribute to sea-level rise, more frequent and intense heatwaves, wildfires, and droughts affecting biodiversity, water supply, and human health. Changes in precipitation patterns also lead to extreme weather events i.e., hurricanes, floods, and heavy rainfall, disrupting ecosystems and human societies[37]. It also negatively impacts biodiversity, as species must adapt, migrate, or face extinction due to altered habitats and shifting climate zones[36]. Addressing climate change requires global cooperation and robust policies aimed at reducing greenhouse gas emissions which include the use of eco-friendly approach, for instance, keeping the environment intact with native plants i.e., perennials grasses[43]. Perennial grasses (e.g., turfgrass) are considered potential for mitigating the effects of climate change because they have a high carbon sequestration capacity, storing carbon in both soil and aboveground biomass[44−46]. They can contribute to reducing greenhouse gas levels by absorbing and storing carbon dioxide from the atmosphere in their roots and tissues, thus helping to mitigate climate change[44]. Furthermore, their capacity to minimize greenhouse gas emissions through reduced tillage and increased nitrogen use efficiency makes them an important component of habitat restoration to mitigate climate change impacts[43].

Consequently, native perennial grasses have been recommended by various previous studies to be used for habitat restoration, including rangelands, because of their physiological and morphological traits, which have shown great potential to improve soil health and biodiversity, mitigate climate change, and combat IAPs[1,5,8,27,40,47]. By their competitive and morphological traits, several perennial native grass species found in African rangelands (e.g., African foxtail grass (*Cenchrus ciliaris*), horsetail grass (*Chloris roxburghiana*), rhodes grass (*Chloris gayana*), *E. superba*, and *E. macrostachyus*) and *P. virgatum*, *S. nutans*, *S. scoparium,* and *A. gerardii* in North America have been tested and recommended for ecological restoration[1−5].

## Perennial grasses as natural allies of soil health

Preceding studies have demonstrated that perennial grasses have the potential to improve soil health and structure in rangelands and protected habitats[1,48−50]. Unlike annual plants, which have shallow root systems, perennial grasses can penetrate deep into the soil, sometimes reaching depths of several meters as they have deep and extensive root systems[1,7,40]. These deep roots create channels that enhance soil aeration, allowing for better oxygen flow and water infiltration, thereby preventing soil compaction[49]. Perennial grasses contribute to soil stability by binding soil particles together, thereby preventing erosion (Fig. 1), which is important in ecosystems or habitats prone to heavy rainfall or wind[48,49]. This stabilization effect reduces the loss of topsoil, which contains the highest concentration of organic matter and nutrients essential for plant growth[44]. Moreover, perennial grasses have been reported to be efficient in nutrient cycling, a critical process for maintaining soil fertility[49]. For instance, their deep roots access nutrients in deeper soil layers, which might be unavailable to shallow-rooted plants[49,50]. These nutrients are then brought to the surface and incorporated into the plant biomass. When the grasses die back or shed leaves, these nutrients are returned to the soil surface as organic matter, making them accessible to other plants[32,49,51]

Furthermore, perennial grasses enhance soil health and structure (Fig. 1), improving the soil's ability to retain water and withstand extreme weather events i.e., heavy rainfall and floods[44,49]. Their extensive root networks stabilize the soil, reducing erosion and runoff (Fig. 1), which are critical for maintaining soil fertility and agricultural productivity under variable climatic conditions[51]. The continuous growth and decay cycle of perennial grasses contributes to the slow but steady release of nutrients[52]. This slow release is beneficial for maintaining a stable nutrient supply, as opposed to the rapid nutrient depletion often seen in soils dominated by annual crops[50]. This process also helps in reducing nutrient leaching, where nutrients are washed away from the soil profile, particularly nitrogen, which is critical for plant growth[49]. Perennial grasses help to reduce $N_2O$ emissions; excess nutrients can lead to increased $N_2O$ emissions[10,11,53]. They also contribute significantly to the soil organic matter, which is a key component of soil health[52]. Organic matter consists of decomposed plant and animal residues, which improve soil structure, water retention, and nutrient availability[50,52]. The biomass produced by perennial grasses, both above and below ground, adds a substantial amount of organic material to the soil[52]. As the plant material decomposes, it forms humus, a stable form of organic matter that enhances soil structure by increasing its capacity to hold water and nutrients[52,54]. This is particularly important in dry regions e.g. in Africa, where water retention can be a limiting factor for crop growth[49]. The organic matter also provides a habitat and food source for a diverse array of soil organisms, including bacteria, fungi, and earthworms, which further contribute to soil fertility through their biological activities[43,52,54].

## Perennial grasses as natural allies of soil biodiversity

Perennial grasses play a crucial role in enhancing soil biodiversity (abundance and diversity) and activities within the soil[31,32,51,54]. They provide critical habitats for soil fauna i.e.,

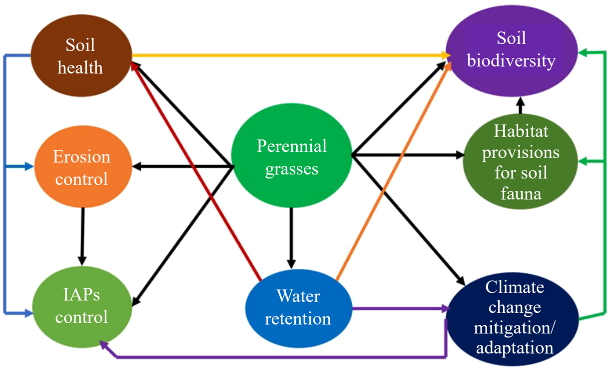

**Fig. 1** Diagram illustrating the multifaceted benefits of perennial grasses and their interconnected roles in promoting soil health, biodiversity, IAPs control, climate change mitigation, water retention, erosion control, and habitat provision. The arrows illustrate the complex interactions and synergies among these components, emphasizing the comprehensive ecological contributions of perennial grasses. The central position of perennial grasses highlights their pivotal role in these areas. This visual representation emphasizes how perennial grasses contribute to and enhance various aspects of ecosystem health and stability.

earthworms, nematodes, and arthropods (Fig. 1)[32,54]. Their complex root systems create a stable environment that supports a wide range of soil organisms[55]. Also, the root systems of perennial grasses exude a variety of organic compounds, including sugars, amino acids, and organic acids, which serve as food sources for soil biodiversity[54]. This continuous supply of root exudates and a stable environment fosters a diverse macro and microbial community, which is essential for maintaining soil health[31,43,54]. For instance, it was reported by Smith et al.[54] that in areas with abundant perennial grasses, a high soil macrofaunal biodiversity (i.e., Lumbricidae, Isopoda, and Staphylinidae) was observed. They further asserted that these grasses were beneficial to soil macrofauna as they increased the abundance and species diversity of staphylinid beetles, woodlice, and earthworms. In addition, Mathieu et al.[56] reported the influence of spatial patterns of perennial grasses on the abundance and diversity of soil macrofauna in Amazonian pastures. These findings suggest that well-managed perennial grasses are vital in enhancing soil macro and microbes in ecosystems[54–56].

These soil organisms perform various functions, including decomposing organic matter, fixing atmospheric nitrogen, and suppressing soil-borne diseases[29,30,32]. A diverse soil macro and microbial community can enhance nutrient cycling, making nutrients more available to plants[30,56]. Enhanced microbial diversity by perennial grasses contributes to the suppression of pathogens through competition and the production of antimicrobial compounds, thus promoting plant health[32]. They also help in maintaining soil structure, fertility, and overall ecosystem function[32]. For instance, earthworms, often referred to as 'ecosystem engineers', augment soil structure by creating burrows that improve aeration and water infiltration in perennial grass communities[31,51]. Their activity also helps mix organic matter into the soil, promoting nutrient cycling[31,32]. Nematodes and arthropods which feed on perennial grass species contribute to the decomposition process, breaking down organic matter and releasing nutrients that are vital for plant growth[31,54]. The presence of a diverse soil fauna community is indicative of a healthy soil ecosystem, which is more resilient to environmental stresses and disturbances[31].

Furthermore, perennial grasses are considered as being instrumental in promoting plant-soil symbiotic relationships[43,54], which are crucial for plant health and soil fertility. One of the most well-known symbiotic relationships is between plants and mycorrhizal fungi[29,33]. These fungi colonize plant roots and extend their hyphae into the soil, increasing the root surface area and enhancing the plant's ability to absorb water and nutrients, particularly phosphorus. The relationship between perennial grasses and mycorrhizal fungi is mutually beneficial. The fungi receive carbohydrates produced by the plant through photosynthesis, while the plant gains improved access to soil nutrients and increased resistance to soil-borne pathogens[30]. This symbiotic relationship is particularly important in nutrient-poor soils, where mycorrhizal associations can significantly enhance plant growth and survival. Additionally, perennial grasses promote other beneficial plant-soil interactions, such as those involving nitrogen-fixing bacteria. These bacteria form nodules on the roots of certain perennial grasses, converting atmospheric nitrogen into a form that plants can use[29,30]. This process is essential for maintaining soil fertility, especially in ecosystems where nitrogen is a limiting nutrient.

## Perennial grasses in climate change mitigation

Perennial grasses are increasingly recognized for their role in climate change mitigation (Fig. 1)[43,44,57]. They can sequester carbon, reduce greenhouse gas emissions, and adaptation to climate variability[58,59]. Their deep root systems and grass-like characteristics make them highly effective in capturing and storing carbon[44]. These roots can penetrate deep into the soil and store carbon for extended periods[59]. Because of this, perennial grasses show potential to enhance the resilience of ecosystems to changing climatic conditions[44]. The roots of perennial grasses are more extensive and persistent compared to annual crops, allowing for greater carbon storage both in the root biomass and the soil[45,46,60]. This process of carbon sequestration involves capturing atmospheric carbon dioxide ($CO_2$) through photosynthesis and storing it in perennial grass tissues (e.g., turfgrasses) and soil organic matter[44–46]. Preceding studies have further shown that perennial grasses can sequester substantial amounts of carbon, contributing to the reduction of atmospheric $CO_2$ levels[45,61]. In addition to carbon sequestration, perennial grasses can reduce greenhouse gas emissions through various mechanisms[43]. One of the primary ways is by reducing the need for frequent soil tillage, which is common in annual cropping systems. Tillage disrupts soil structure, releases stored carbon as $CO_2$, and increases soil erosion[58,61]. Thus, with their long lifespan, perennial grasses can reduce the need for tillage, thereby minimizing $CO_2$ emissions from soil disturbance[43,58].

Moreover, perennial grasses can improve nitrogen use efficiency, reducing the need for synthetic fertilizers that are a major source of nitrous oxide ($N_2O$) emissions—a potent greenhouse gas[53,62]. Their deep root systems enable them to access nutrients from deeper soil layers, reducing nutrient leaching and the subsequent emissions of $N_2O$[53]. By optimizing nutrient use, perennial grasses contribute to lower greenhouse gas emissions associated with agricultural practices[63]. Also, perennial grasses are crucial for adapting to climate variability[44]. Their deep root systems allow them to access water from deeper soil layers, making them more resilient to drought conditions compared to annual crops[44]. This water use efficiency helps maintain plant growth and productivity even during periods of water scarcity, which are expected to become more frequent with climate change[49]. In general, perennial grasses support soil biodiversity conservation through habitat provision, climate change mitigation, and promoting ecosystem resilience[58]. Besides, these grasses are crucial for ecosystem stability and productivity, particularly in the face of climate change, and ensure the continued provision of ecosystem services (Fig. 1).

## Perennial grasses in combating invasive plants

Previous studies have shown that IAPs pose significant threats to ecosystems worldwide by displacing native species, altering habitats, and disrupting ecosystem functions and services[15,20,23,64]. Among the integrated management techniques to combat IAPs involves the use of competitive native plants (Fig. 1) such as perennial grasses[6,7,40]. These grasses, which live for more than two years with robust root systems, growth, and resilience to varying environmental conditions, offer several advantages in controlling IAPs[1,48]. Their competitive growth patterns and ability to restore and maintain native plant communities, and establish, and thrive in diverse habitats make them formidable competitors against invasive plants[1]. One of the primary ways perennial grasses combat IAPs is through competition for resources[48]. Their extensive root systems allow them to efficiently absorb water and nutrients, outcompeting IAPs that typically have shallower roots. This competitive edge limits the resources available to IAPs, inhibiting their growth and spread. For instance, species like *P. virgatum* and big *A. gerardii* are known for their deep roots, which can reach depths of up to 10 feet (3 m), providing them with a significant advantage over many IAPs[8,48]. They can also outcompete IAPs through their competitive growth patterns including quick establishment and forming dense canopies that shade out AIPs[1,8]. For example, native perennial grasses like *S. nutans* and *S. scoparium* have been shown to effectively compete with invasive species i.e., spotted knapweed (*Centaurea stoebe*) by limiting light availability and space for growth[8,48].

Moreover, using their extensive root systems that stabilize the soil, perennial grasses can prevent erosion and invasions of IAPs[44]. Invasive plants i.e., carrot weed (*Parthenium hysterophorus*), cheatgrass (*Bromus tectorum*), and kudzu (*Pueraria montana*) can rapidly colonize disturbed soils, leading to severe erosion problems[20,65,66]. However, perennial grasses i.e., *P. virgatum* and big *A. gerardii* have been found to reduce erosion and creating an unfavorable environment for IAPs to establish owing to their deep fibrous root systems that hold the soil in place. Perennial grasses can also modify the microenvironment in ways that make it less conducive for IAPs[1,27,66]. They produce dense root mats that strengthen the organic matter content and soil structure, improving the fertility and health of the soil. The diversity and growth of native plant species is aided by improved soil conditions, which further promote biodiversity and inhibit IAPs by strengthening ecosystem resilience[48].

Additionally, the use of perennial grasses in restoration has shown promising results in reclaiming areas overrun by IAPs and maintaining native plant communities that are disrupted by IAPs[8,66]. By planting a mix of native perennial grasses, land managers can restore ecological balance and prevent the re-establishment of IAPs[26]. These grasses provide long-term ground cover and habitat for wildlife, contributing to the overall health and stability of the ecosystem[1,8,54]. By reintroducing native perennial grasses into areas (e.g., rangelands and protected habitats) dominated by IAPs, ecosystems, and their biodiversity can be restored to their earlier conditions[27,39,67]. For instance, the use of native perennial grasses has been successful in restoring prairie ecosystems that were previously overrun by IAPs i.e., leafy spurge (*Euphorbia esula*) and purple loosestrife (*Lythrum salicaria*)[68]. Another important example of using perennial grasses to mitigate IAPs is the restoration of tallgrass prairies in the Midwest United States[8,66]. These prairies were historically dominated by native perennial grasses i.e., *S. nutans* and *S. scoparium*, however IAPs i.e., smooth brome (*Bromus inermis*) and reed canarygrass (*Phalaris arundinacea*) displaced them, leading to biodiversity loss and altered ecosystem functions[8,66,68]. Studies show that following the restoration of these invaded habitats using perennial grasses, native grasses successfully reestablished and reduced IAPs and promoting native biodiversity[66,67]. In addition, another notable example is the use of perennial grasses to restore riparian areas which were heavily invaded and impacted by IAPs i.e., giant reed (*Arundo donax*) and saltcedar (*Tamarix spp.*)[67,69]. Planting native perennial grasses like western wheatgrass (*Pascopyrum smithii*) and creeping wildrye (*Elymus triticoides*) in these areas helped to stabilize the soil, reduce erosion, and suppress IAPs, leading to improved riparian habitat quality and ecosystem resilience[18,66,67,69].

Therefore, competitive suppressive perennial grasses are a crucial tool in the fight against IAPs and other weeds. Their competitive abilities, contributions to soil health, and role in ecosystem restoration makes them invaluable in managing and alleviating the impacts of IAPs. As research continues, the potential for perennial grasses to be integrated into broader IAP strategies remain significant, promising a more sustainable and ecologically sound approach to preserving native biodiversity.

## Conclusions

Perennial grasses are pivotal in enhancing soil biodiversity, mitigating climate change, and combating IAPs. Their deep root systems stabilize soils, support diverse soil faunal communities, and improve water retention. Besides, they are important grasses in sequestering carbon, reducing greenhouse gas emissions, suppressing IAPs, and supporting the reestablishment of native plant communities. Integrating perennial grasses into protected areas and rangelands management practices could offer a sustainable solution to pressing environmental challenges including invasions of IAPs. Stakeholders i.e., farmers, conservationists, ecologists, and land managers are advised to use perennial grass systems in their restoration practices, crop rotations, and pasturelands to enhance soil health and resilience. They are further commended to use perennial grasses for erosion control and to improve soil structure and fertility. Policymakers could develop and support policies that incentivize the use of perennial grasses in agricultural and restoration projects. Researchers, they are advised to conduct studies to quantify the long-term benefits of perennial grasses on soil biodiversity and climate change mitigation. Additionally, they can develop country or region-specific guidelines for the effective use of perennial grasses in different ecosystems. Hence, by integrating perennial grasses into our environmental stewardship strategies, we can ensure a thriving, balanced ecosystem capable of withstanding the impacts of climate change and IAPs.

## Author contributions

The author confirms sole responsibility for the following: review conception and design, and manuscript preparation.

## Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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## Conflict of interest

The author declares that there is no conflict of interest.

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