

Multifunctionality of Grassland Soils: Opportunities and Challenges

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1. Introduction

Grasslands are very diverse and their global distribution is determined by the climate, mainly the temperature and precipitation. FAO [1] reported that in 2023, meadows and pastures globally covered 3200 million ha. They are found on all continents except Antarctica, on a wide range of soil types. Temperate grasslands include Eurasian steppes, North American prairies, the pampas lowlands of South America, and Patagonian steppe. Tropical and subtropical savannas occur in Africa and Australia, in the north of South America, in the south of Northern America, and in South Asia and Southeast Asia. These natural grass biomes are under permanent anthropogenic pressure around the world. They are often replaced by intensive agricultural systems [2] and are used as arable land. One of the reasons for this is their high-quality soil, which develops during soil-forming processes thanks to the accumulation of high-quality organic material provided by dead grass bodies. Grasses are generally rich in structural (sugar and starches) and non-structural (cellulose, hemicellulose, pectin, etc.) carbohydrates and contain less protein, minerals, vitamins, and fats in comparison to legumes [3]. They are an excellent prerequisite for high-quality organic matter composition such as that found in the most productive soils on Earth, Chernozems, which only develop in forest–steppe zones [4]. However, grasslands around the world are found on different types of soils, of varying quality, also due to dynamic land use changes. The increased demand for food and fodder results in intensive land utilization. Forests are often being converted into grasslands and pastures, causing significant modifications in soil properties, as reflected in the performance of ecosystem functions and services.

Besides productive functions, grassland soils contribute to a wide range of functions and ecosystem services, including regulating, supporting, and cultural services. They act as carbon sinks [5], contribute to water retention and regulation [6], maintain biogeochemical cycles [7], and are also of major relevance to biodiversity [8].

Despite their importance, grasslands are experiencing widespread and accelerating degradation due to global environmental changes [9], and the percentage of protection for this biome is lower than for all other biomes [10].

Scientists and experts in the field of grasslands are making efforts to increase awareness of the values they offer to humanity, provide new knowledge and improve grasslands' management. They point out their variability, aiming to improve understanding of nutrient cycles and their productivity with the help of sustainable management. They highlight the role of grasslands in dealing with climate change and other environmental risks. Increasing



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attention is also dedicated to new, less explored areas, such as the role of grassland soils' microbiome and its contribution to the provision of ecosystem services.

2. An Overview of Published Articles

This Special Issue of *Agronomy* contains 12 research articles focused on the multifunctionality of grassland soils. These original research papers can be grouped into five categories:

- (1) Variability of grassland soils' properties (contribution 1).
- (2) Grassland soils' nutrients' forms, roots and availability, and factors affecting these (contribution 2, 3, 4).
- (3) Grassland soil carbon and nutrients' management (contribution 5, 6, 7, 8).
- (4) Grassland soils as buffers against environmental and climate stresses (contribution 9, 10).
- (5) Prospective role of microorganisms in grassland soils' processes and functions (contribution 11, 12).

2.1. Variability in Grassland Soils' Properties

Kanianska and Kizeková [1] evaluated the variety of natural conditions and land use patterns (arable land, forest land, and grassland) determining the high variability in soil properties in Central Slovakia. Grasslands situated on alluvial plains were distinguished by the highest biological parameters (earthworm number, biomass and diversity) and a higher capacity for water retention and C and N storage in comparison to other land types, including grasslands situated on slopes.

2.2. Grassland Soil Nutrients' Forms, Roots, Availability and Factors Affecting These

Wei et al. [2] investigated how inorganic nitrogen form regulates nitrogen uptake in *H. altissima* through pot experiments by applying ammonium nitrogen, nitrate nitrogen, mixed nitrogen, and a nitrogen-free control in Songnen grassland ecosystems at the eastern end of Eurasia. Ammonium and nitrate applications reduced soil pH, increased electrical conductivity, and enhanced inorganic nitrogen pools, respectively. Root morphological traits were significantly enhanced under ammonium, nitrate, and mixed nitrogen treatments. Their findings highlight nitrogen form as a key regulator of soil–plant nitrogen coupling.

Yang et al. [3] observed the effect of atmospheric nitrogen on the leaf and root traits of eight perennial grasses in a field experiment, incorporating control and nitrogen addition treatments. Nitrogen addition significantly altered leaf and root trait expression and promoted biomass accumulation in both life forms. Specifically, nitrogen addition increased assimilation rate, leaf nitrogen content, specific root length, and root nitrogen content while markedly reducing the root tissue density of perennial rhizome grass and perennial bunchgrasses. The results indicated a decoupling of above- and belowground resource acquisition strategies at the local scale. Additionally, authors underscored the importance of combining above- and belowground traits to improve predictions of plant performance.

Orešković et al. [4] quantified the soluble, active, and exchangeable forms of K and Mg in two soil types, Cambisols and Luvisols, using grassland ley swards differing in the species composition of their sown mixtures. Thirty-three plant communities were established following a simplex design approach, with sown proportions ranging from 100% (monocultures) to 50%, 33%, 25%, 16.7%, and 0%. Plant diversity only had a slightly negative trend for potassium on Cambisols. Grass-dominated mixtures maintained higher soil K levels as legume-rich swards. Differing effects of the extractants on K regarding indications of the need to use the CaCl_2 and NH_4OAc extraction methods were also observed.

2.3. Grassland Soil Nutrients Management

Wei et al. [5] observed the effect of litter addition on soil organic carbon fractions with intensified grassland degradation in a 240-day incubation experiment using *Leymus chinensis* litter incubated on days 0, 23, 60, and 240. Grassland degradation significantly reduced particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) concentrations; moreover, litter addition in degraded grasslands further reduced soil organic carbon (SOC). In the lightly and moderately degraded grasslands, litter addition modulated POC and MAOC via both microbial and physicochemical pathways. In the highly degraded grasslands, litter addition influenced POC and MAOC not only indirectly, through microbial and physicochemical pathways, but also directly, by promoting MAOC formation. Overall, although litter decomposition altered SOC and its fractions, its effects were constrained by the degree of grassland degradation.

Jarne et al. [6] investigated the nitrogen, phosphorus, potassium and carbon balances under three different types of meadows, as follows: intensive meadows (with high livestock load and inorganic fertilization); semi-extensive meadows (with medium livestock load and organic fertilization); and extensive meadows (with low livestock load and low fertilization rates). Nitrogen was more stable in semi-extensive and extensive meadows, due to its organic form. In contrast, intensive meadows showed higher nitrogen variability depending on the climate. Carbon accumulation was more stable in extensive meadows. Potassium showed a strong response to temperature, and phosphorus appeared as a limiting factor.

Phosphorus is one of the major constraints to karst grassland productivity, as observed by Pan et al. [7]. They investigated the effects of fertilizers and manures on soil bioavailability of phosphorus fractions in karst grasslands and explored the relationship between soil properties and soil phosphorus fractions within an experiment with the four fertilizer applications (control; fertilization; manure application; combined fertilization and manure application). The combined application of fertilizer and manure was the most beneficial measure for enhancing soil phosphorus bioavailability.

Paszkiewicz-Jasińska et al. [8] conducted a field experiment at the Experimental Station in Poznań-Strzeszyn, western Poland, under production conditions with different fertilization regimes, varying in both type and dosage. The treatments included an unfertilized control, mineral fertilization (NPK), farmyard manure (FYM), and alternate NPK/FYM fertilizers. The most balanced nutrient budgets were observed under alternate NPK/FYM fertilization, with moderate surpluses of N and P and a smaller K deficit compared to FYM applied alone. In contrast, inorganic and organic fertilization applied separately resulted in greater nutrient surpluses or a pronounced potassium deficit. This study showed how alternating FYM and mineral NPK can maintain productivity and reduce environmental impacts.

2.4. Grassland Soils as Buffers to Environmental and Climate Stresses

Climate changes accompanied by heat waves (HWs) threaten grassland ecosystems. Shao et al. [9] conducted an in situ spring and summer HWs simulation experiment combined with a locally common human disturbance (mowing) to separate soil respiration (R_s) into autotrophic respiration (R_a) and heterotrophic respiration (R_h) on a natural Eurasian meadow steppe. HWs significantly affected grassland R_s , R_h and R_a and also interacted with mowing, but the effect of spring HW and summer HW were different. R_s , R_h and R_a were inhibited by spring HWs but promoted by summer HWs. The results indicated that time changes in HWs have widely divergent influences on the ecosystem, and mowing would decrease the anti-interference ability of the ecosystem.

Bogunovic et al. [10] showed how grassland soils are important components of urban green areas and croplands in the peri-urban area of Zagreb, exhibiting multifunctional

benefits, including high organic matter content, improved bulk density and active carbon storage. The presence of permanent vegetation cover contributed to the high capacity for climate and water regulation and carbon sequestration. The results emphasize the importance of protecting and managing grasslands as an important component of urban green areas. Practices such as mulching, minimal disturbance and continuous cover can maximize the resilience to climate change and the ecosystem services of grassland soils.

2.5. Perspective Role of Microorganisms in Grassland Soils Processes and Functions

Chen et al. (contribution 11) found out that shrub plantations on mobile sand dunes are an effective strategy to combat desertification in semi-arid regions. Herbaceous communities developing beneath these plantations enhance ecosystem stability and improve revegetation outcomes. They investigated the structural responses of soil bacterial communities, key functional genes, and plant–soil–microbe interactions across an herbaceous vegetation succession gradient under *Caragana microphylla* sand-fixation plantations in the sandy Horqin Grassland. Plant species richness, diversity, and biomass increased progressively with succession. Concurrent improvements in soil nutrients and enzymatic activities were observed. The most influential factors for soil bacterial community were pH and organic matter. These findings highlight plant–soil–microbe interactions as intrinsic drivers of vegetation succession in desertified ecosystems.

Yangzom et al. (contribution 12) investigated whether lignin is labile or resistant to biological and chemical degradation in soil, particularly in alpine ecosystems. They analyzed the relationship between phospholipid fatty acid biomarkers and the abundance of lignin components in grassland soils from North Tibet, China. They collected soil samples and measured the relative abundance of lignin before and after a 210-day incubation period. They found out that the relative abundance of lignin in the alpine grassland soils decreased during the incubation period. Significant relationships were found between the phospholipid fatty acid biomarkers of bacteria, fungi, Gram-positive bacteria, and Gram-negative bacteria and the relative abundance of lignin components. This study contributed to the understanding of soil organic matter degradation and the dynamics of microbial communities in alpine grassland soils in the context of future global warming.

3. Conclusions

Healthy soil, a non-renewable resource, is fundamental to sustaining grassland ecosystem services and ensuring the long-term resilience of agricultural landscapes. This Special Issue demonstrates that grassland soils support a wide range of ecological, environmental, and socio-economic functions that remain insufficiently recognized in both research and policy. The research articles collected here underline the importance of interdisciplinary research for improving our understanding of grassland soil multifunctionality and for developing evidence-based management strategies. We hope that this Special Issue will stimulate further research, strengthen collaboration among scientists and practitioners, and support the integration of soil multifunctionality into sustainable grassland management and policy development.

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