Climatic Change (2023) 176:55
https://doi.org/10.1007/s10584-023-03537-w

ESSAY

Carbon sequestration potential and the multiple functions of Nordic grasslands

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Received: 8 November 2022 / Accepted: 15 April 2023 / Published online: 4 May 2023

Abstract

Grasslands are important carbon sinks, but the underlying processes for their soil carbon sequestration potential are still not well understood, despite much attention given to this topic. In Europe, grasslands, especially semi-natural grasslands, are also important for promoting biodiversity. Moreover, recent global reports have highlighted the importance of biodiversity in supporting climate actions. In boreal and alpine regions in the Nordic countries, grasslands also play an important role in milk and meat production and food security. Certain grassland features and management practices may enhance their soil carbon sequestration potential. Semi-natural grasslands maintained by optimized livestock grazing are vital for aboveground biodiversity and show promise for belowground biodiversity and carbon sequestration potential. It is essential to assess the multiple functions of grasslands, particularly semi-natural grasslands, to facilitate the optimization of policy measures across policy areas. Climate and biodiversity policies should not counteract each other, as some do today. This essay addresses the multiple functions of grasslands and calls for more knowledge about carbon sequestration in Nordic grasslands. This will enable the management of these ecosystems to align with climate mitigation, maintain biodiversity, and satisfy the global need for increased food supply.

Keywords Grasslands · Semi-natural grasslands · Soil carbon · Climate change · Grazing · Greenhouse gases · Biodiversity · Food security

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1 Introduction

The potential of grassland soil carbon sequestration has gained increasing attention (Lorenz and Lal 2018). A recent review by Bai and Cotrufo (2022) estimated that grasslands store approximately one-third of the world's terrestrial carbon stocks. Several European grassland studies also support the idea that grasslands can serve as important carbon sinks (Chang et al. 2015, Chang et al. 2016). The Food and Agriculture Organization of the United Nations (FAO) (2017) likewise emphasizes the substantial potential of grasslands to provide large and stable soil carbon sinks.

The carbon sequestration potential of grasslands, however, remains a subject of debate. Röös et al. (2017) claimed that this potential is limited while Godde et al. (2020) questioned "overly optimistic expectations" and stressed the high context dependency of soil carbon sequestration rates in grasslands. Factors such as climate, vegetation type, soil type and quality, the composition of soil biological communities, and management practices all influence carbon sequestration potential (Garnett et al. 2017). A Mediterranean study emphasized the need for region-specific data on grassland soil carbon to reflect differences in climatic and agricultural conditions and called for a strategic plan to extend on-site field measurements (Aguilera et al. 2021). Their analysis highlights the necessity for refining carbon footprint estimation methods in life cycle assessments of agricultural products, including region-specific data on relevant processes, such as soil carbon sequestration.

Grasslands have, however, multiple functions, including providing habitats for biodiversity. The global report from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019) highlights the importance of biodiversity conservation as loss of biodiversity is as crucial as climate change. The land report from the Intergovernmental Panel for Climate Change (IPCC 2019), the global IPCC 2022 report (IPCC 2022), and the UN Biodiversity Conference (COP 15) in December 2022 have also pointed to the connections between the climate and biodiversity crises, highlighting the importance of biodiversity and other ecosystem services to counteract and adapt to climate changes, and the need for alignment of climate policy measures to support biodiversity. Loss of biodiversity is intensifying, with potential negative consequences for ecosystem services, including the capacity of ecosystems for climate mitigation and adaptation to climate changes. Newbold et al. (2016) assessed that land use pressures have reduced grassland biodiversity beyond the planetary boundary suggested as a safe limit, indicating that continuing biodiversity loss will undermine efforts toward long-term sustainable development. The IPBES and IPCC reports call for the development of a mix of policy instruments to motivate private and public decision-makers to implement both climate mitigation and biodiversity conservation measures while maintaining high levels of other ecosystem services.

In addition to their importance for biodiversity and for carbon sequestration, grasslands can also play an important role in food security, especially in the Nordic countries, where cultivation is constrained by climatic factors. While the potential for carbon sequestration in grasslands worldwide largely lies in the restoration of degraded grasslands, large areas of Nordic grasslands remain, although they are under pressure from forest regrowth due to lack of grazing to maintain the open grasslands. In this context, this essay draws attention to the importance of grasslands for soil carbon sequestration and biodiversity conservation, as well as for other ecosystem services, such as grazing resources. Specifically, we discuss whether grassland management for biodiversity and food production may have the co-benefit of climate mitigation through increased soil carbon sequestration. Since regional differences are important for these complex interactions, we will focus the discussion on Europe and especially Nordic grasslands.

2 Grasslands in Europe

Grasslands are herbaceous vegetation types mostly dominated by grasses (*Poaceae*) or other graminoids (*Cyperaceae, Juncaceae*) and with a relatively dense vegetation cover (>25 % surface cover) (Dengler et al. 2014). They are often transitional ecosystems maintained at a stable successional stage by disturbances such as grazing, mowing, or fire (Norderhaug et al. 1999; Fuhlendorf et al. 2006; Ratajczak et al. 2014; Scasta et al. 2016). In Europe, grasslands can be classified as natural, semi-natural, or cultivated. Natural grasslands occur in areas where forest development is not possible due to dry or cold conditions or other factors that prevent tree growth. However, such areas are rare in Europe today, with small pockets of "genuine" steppe found in Ukraine and Romania (Emanuelsson et al. 2009). On the other hand, semi-natural and cultivated grasslands have been developed by human management in naturally forested areas. These grasslands require human intervention to prevent overgrowth by trees. Semi-natural grasslands, which were created through low-intensity grazing or hay production, are often species-rich. Some of the semi-dry and base-rich semi-natural grasslands found in Europe hold the world record for vascular plant-species richness on small scale (e. g. 89 species on $1m^2$) (Wilson et al. 2012; Habel et al. 2013). However, both natural and semi-natural grasslands in Europe have increasingly been converted to cultivated grasslands that are fertilized and intensively managed for grazing or for hay production, resulting in a loss of biodiversity (Bignal and McCracken 1996; Pykäla 2007).

3 Characteristics of grasslands with high potential for soil carbon sequestration

Certain grassland characteristics and management strategies may be particularly important for promoting or reducing soil carbon sequestration potentials. Here, we present some key points that summarize these characteristics and strategies, with a call for more research.

3.1 Highly developed root systems and high belowground biomass allocation

Grassland plant species are adapted to grazing and mowing through a low apical growth point, high allocation of biomass belowground, and a root/shoot ratio that is about 10 times higher than in forests (Jackson et al. 1996). The depth distribution of roots is a critical factor in the storage and stabilization of root carbon in the soil (Poirier et al. 2018). In fact, grassland soil carbon is often largely composed of root-derived carbon (Martinez et al. 2016; Yang et al. 2021). As the mean residence time of root carbon increases with soil depth (Rasse et al. 2005), deeper-rooted plants may be particularly effective at sequestering carbon in the soil (Sosa-Hernández et al. 2019). In addition, the organic matter in the subsoil contains more microbial-derived compounds than topsoil organic matter, which can be integrated into mineral-associated soil organic fractions with especially long mean residence (Rumpel and Kögel-Knabner 2011; Sosa-Hernández et al. 2019).

3.2 High aboveground and belowground biodiversity

Increasing plant species diversity can increase root biomass and root exudates, potentially promoting microbial necromass contribution to soil organic storage (Bai and Cotrufo 2022). In a 4-year managed grassland experiment with a biodiversity gradient ranging from one to 60 species, it was shown that carbon storage increased with sown species richness (Steinbeiss et al. 2008). Additionally, manipulation of species richness in a 19-year grassland experiment showed that increasing plant species richness enhanced carbon storage (Pastore et al. 2021). Aboveground biodiversity influences belowground diversity (Chen et al. 2018), and vice versa. For example, arbuscular mycorrhizal fungal diversity can increase plant diversity in grasslands, although the mycorrhizal community composition seems to be more important than the richness per se (Koziol and Bever 2019). However, the knowledge about the relations between aboveground and belowground biodiversity remains limited (De Deyn et al. 2005). Belowground biodiversity is however of high importance for carbon and nutrient cycling processes, and diversity across groups of organisms plays a decisive role in fully maintaining these processes (de Graaff et al. 2015).

3.3 Mycorrhiza

Most grassland plants live in symbiosis with arbuscular mycorrhizal fungi, which depend on recent plant photosynthates for their growth and activity. Arbuscular mycorrhizal fungi colonize plant roots and form soil mycelia that scavenge for nutrients in larger soil volumes and smaller soil pores than roots (Sosa-Hernández et al. 2019). Some of the nutrients, particularly nitrogen, phosphorus, and sulfur, taken up by arbuscular mycorrhizal fungi are transported to the roots and may stimulate plant growth. Meanwhile, some nutrients are immobilized, along with carbon, in living and dead soil mycelium (Giovannetti et al. 2017). Therefore, the mycorrhizal mycelium provides a direct pathway for recently fixed carbon into the soil matrix. This is in contrast to free-living saprotrophic organisms that rely on carbon from decomposing organic material for their metabolism and thus elicit a net loss of soil carbon. Arbuscular mycorrhizal mycelium can also promote aggregate stability, leading to improved soil structure and carbon sequestration (Lehmann et al. 2017). However, even though arbuscular mycorrhizal fungi lack the ability to decompose complex organic matter (Tisserant et al. 2013), they may still enhance decomposition and nutrient mineralization by stimulating saprotrophic organisms (Jansa et al. 2019). Therefore, the net effects of arbuscular mycorrhiza on soil carbon stocks in different types of grasslands are not yet well understood, although they likely have a positive long-term effect on soil carbon stocks, particularly in the subsoil (Sosa-Hernández et al. 2019, Lehmann et al. 2017).

3.4 Optimal grazing pressure

Grazing stimulates the accumulation of soil organic carbon by promoting root growth and turnover and by defoliation, which provides large inputs of organic matter to the soil (Ziter and MacDougall 2013). For example, Allard et al. (2007) found that 3 years of grazing in a French upland semi-natural grassland promoted the carbon sink, regardless of grazing intensity and fertilization. However, a meta-analysis in 17 grasslands worldwide showed that the grazing effect on carbon storage depends on grazing intensity, environmental conditions, such as precipitation and soil texture, and the types of grasses (classified as grasslands dominated by C_3 grasses, C_4 grasses, or a mixture of both) (McSherry and Ritchie 2013). C_3 and C_4 grasses have different photosynthetic pathways, and grazing impacts their root structure differently. European grasslands are predominantly C_3 grasslands (de Deus et al. 2021; Still et al. 2003). In general, soil carbon sequestration is positively correlated with grazing intensity in C_4 grasslands and negatively in C_3 grasslands (Garnett et al. 2017). Exploring interactions between grass type and grazing McSherry and Ritchie (2013) found that for C_3 grasses, grazing had a positive effect on soil organic carbon only at light grazing intensities, and this effect became negative at moderate to heavy grazing intensities.

While light to moderate intensity grazing is more likely to maintain soil carbon stocks and has greater potential to enhance sequestration, heavy grazing reduces plant growth, destroys the plant cover, and causes soil carbon losses (Garnett et al. 2017). Studies indicate that moderate-intensity grazing promotes soil carbon sequestration more than no grazing or high-intensity grazing (Ziter and MacDougall 2013; Chang et al. 2016). A nationwide survey of permanent grasslands in England confirmed that moderate management (grazing and fertilizing) resulted in the greatest soil carbon stocks (Ward et al. 2016). Some studies even conclude that carbon sequestration in grazed grasslands partly, or under specific conditions, entirely offsets greenhouse gas (GHG) emissions from livestock (Bellarby et al. 2013; Godde et al. 2020). Recent studies indicate that optimal grazing practices, such as optimal timing and numbers of livestock and moving ruminants between pastures to avoid overgrazing, may facilitate soil carbon sequestration (Stanley et al. 2018; Teague and Kreuter 2020). Moving grazing animals between pastures is a key aspect of sustainable management. Without fencing, grazing animals naturally move between pastures. Observations of dairy cows on mountain summer pastures in Norway indicate that they cover large areas during grazing, and traditional cow breeds moved longer distances (Hessle et al. 2014); this prevents overgrazing. The contrasting results on grazing and soil carbon sequestration potential illustrate the importance of considering the specific agro-ecological conditions (Garnett et al. 2017).

3.5 Sensitivity to physical soil disturbance and fertilization

Ploughing and tilling practices to revitalize grasslands and increase yield typically result in loss of soil carbon. According to Jastrow et al. (2007), reducing soil organic carbon turnover by minimizing soil disturbance through tillage or erosion is crucial for enhancing carbon sequestration. Converting of grasslands into cropland also results in loss of soil carbon. Poeplau et al. (2011) showed that 17 years after grasslands were converted to annual croplands, more than a third of their soil organic carbon stocks had been lost. In contrast, establishing grasslands on former croplands led to continuously increasing soil organic carbon for more than 100 years and a higher gain in soil organic carbon than when converting cropland to forest. This finding was confirmed by a literature review conducted by Conant et al. (2017). Moreover, fertilization can increase plant biomass and may therefore further promote soil carbon sequestration in non-tilled, permanent grasslands (Karltun et al. 2010). In a study of chronic nitrogen fertilization of permanent grasslands, Cenini et al. (2015) found that heavy (organo-mineral) but not light (organic) soil density fractions showed increased soil carbon sequestration. However, inputs of nitrogen and phosphorous to grasslands lead to changes in the taxonomic and functional composition of soil microbial communities (Leff et al. 2015), which can influence the entire belowground ecosystem. Hence, practices that affect soil organisms, such as soil disturbance and fertilization, are likely to also affect soil organic matter dynamics, since these are tightly linked to the nutrient and carbon needs of the soil organisms (Janzen 2006).

4 Potential for carbon sequestration in grasslands

The characteristics that may support the potential of grasslands for soil carbon sequestration appear to be closely aligned with those of semi-natural grasslands, and to a large extent, natural grasslands. This suggests that semi-natural grasslands may have a good potential for carbon sequestration and potentially a higher soil carbon content than cultivated grasslands, although this has not been clearly documented. Many scientific papers discussing soil carbon sequestration and carbon stocks in grasslands do not specify the type of grassland studied. Permanent grasslands can be either improved, fertilized grasslands or semi-natural grasslands.

Semi-natural grasslands are the result of low-intensity agricultural practices that have been in place for a long time (Dengler et al. 2014). Over this time, they may have developed considerable root systems and built up large soil carbon stocks, while the carbon sequestration rate has diminished successively and approached an equilibrium (Garnett et al. 2017). This equilibrium may be maintained as long as the management remains unchanged (Garnett et al. 2017). On the other hand, the management of cultivated grasslands may vary from year to year, giving less opportunity for root system development. However, permanent improved grasslands may have better developed root systems. Further, most of the plant species in semi-natural grasslands are associated with arbuscular mycorrhizal fungi (Norwegian Biodiversity Information Centre 2019) which probably improve soil carbon sequestration (Sosa-Hernández et al. 2019). In contrast, cultivated grasslands tend to have lower abundance of mycorrhizal fungi (Schnoor et al. 2011; Bowles et al. 2016, House and Bever 2018), although we do not know at which timescales permanent grasslands may reestablish biodiversity and characteristics of semi-natural grasslands.

In Europe, most remaining semi-natural grasslands are grazed. Several studies have shown that overgrazing causes loss of soil carbon stock and that light to moderate grazing could maintain soil carbon stocks and have a greater potential for soil carbon sequestration than heavy or too light grazing (Garnett et al. 2017). A study of sheep grazing on low-alpine grasslands in Norway found that 7 years of grazing had little impact on soil carbon stocks, with high sheep stocking rates causing a small decrease and low stocking rates causing no or a slight increase (Martinsen et al. 2011). Furthermore, another study of lightly grazed grassland, *Empetrum*-dominated heath, and *Salix*-shrub-dominated vegetation in the Norwegian mountains showed that grassland had the largest total ecosystem carbon pool (Sørensen et al. 2018). In alpine regions, semi-natural and natural grasslands may have quite stable and substantial stocks of soil carbon (Castano et al. 2022), but at the same time, may have limited potential for additional, short-term sequestration because soil processes are slow. However, alpine grasslands store more of the soil carbon in particulate form, often forming an organic topsoil, while temperate grasslands store relatively more carbon in mineral-associated organic matter in the subsoil. An interesting avenue for further research thus is to unravel mechanisms of carbon storage in organic topsoils versus mineral subsoils across climatic gradients, since minerals can get saturated with organic matter, while carbon storage in particulate organic matter has no such limit (Bai and Cotrufo 2022).

Cultivated grasslands are more productive than semi-natural grasslands due to their higher nitrogen and phosphorous content, which allows for increased grazing animals and stimulation of aboveground biomass production and root growth. While fertilization of cultivated grasslands generally increases soil carbon stocks by stimulating plant growth, fertilization of semi-natural grasslands reduces biodiversity (Emanuelsson et al. 2009). As semi-natural grasslands are of high importance for biodiversity, management strategies aimed at increasing soil carbon stocks, such as fertilization, may not be suitable for sustainable management of these ecosystems.

5 Climate policy in synergy with other sustainable development goals: biodiversity and food production

Semi-natural grasslands play an important role in maintaining European biodiversity (Pykälä 2007). However, in Western Europe, the area of this type of ecosystem has significantly decreased due to factors such as intensification of agriculture, abandonment of traditional agricultural practices, and land conversion. This trend has resulted in long red lists of endangered species of plants, fungi, insects, birds, and other animals that depend on semi-natural grasslands. In Norway, for instance, 29% of the threatened species live in semi-natural habitats of grasslands and coastal heathlands (Norwegian Biodiversity Information Centre 2021), while in Sweden, semi-natural habitats are critical for 34% of red-listed species (SLU Swedish Species Information Centre 2020), and in Finland, for 24% (Finland's Environmental Administration 2019). The trends for grassland biodiversity are negative, and more and more species are being red listed (Jakobsson and Pedersen (eds.) 2020; IPBES 2019), emphasizing the need to preserve remaining semi-natural grasslands to prevent further loss of biodiversity.

Furthermore, maintaining semi-natural grasslands can help preserve existing carbon stocks in the ground (Garnett et al. 2017), keep the landscape open, and contribute to a higher albedo effect. Although albedo is not included in the reporting guidelines of the United Nations Framework Condition on Climate Change (UNFCCC), Bonan et al. (2008) emphasized that albedo can have large effects on climate feedbacks at northern latitudes. Compared to grasslands, boreal forests have lower albedo and absorb more solar radiation, contributing to temperature increase in the atmosphere. Therefore, understanding the importance of grasslands *versus* forests for albedo in the context of climate mitigation, especially in the Nordic countries and other boreal regions, is essential.

Semi-natural grasslands need to be recognized for their multiple functions. To balance climate mitigation and grassland biodiversity preservation, Burrascano et al. (2016) suggest aligning decision-making across policy sectors, focusing on a range of ecosystem services and biodiversity issues, and valuing extensively managed (low-intensity) ecosystems for their multiple functions. The current agricultural policy in the EU lacks attention to the management of permanent grasslands, which is crucial for their environmental benefits (Pe'er et al. 2014).

The roles of grasslands differ among regions. In northern and alpine regions of Europe, where crop production is constrained by climatic and ecological conditions, grasslands play an important role in meat and dairy production (Nordic councils of Ministers 2017). Grazing ruminants can utilize grasslands which cannot be cultivated but still can contribute to food for humans. In the Nordic countries, particularly in mountainous Norway where only 3% of the total land is cultivated, the areas of rangeland with semi-natural and natural grasslands are vital for improving the self-sufficiency and ensuring more reliable food security (Nordic Council of Ministers 2017). The World Resources Institute (2019) emphasizes the responsibility of all countries to utilize their possibilities for food production to secure a sustainable food future.

IPBES (2019) highlights that activities aimed at mitigating climate change carry the risk of negative side effects for biodiversity and food security. Afforestation, an important aspect of EU climate policy, is one such activity that has been criticized for loss of biodiversity, particularly when semi-natural grasslands are afforested (Burrascano et al. 2016; Veldman et al. 2019). In addition, afforestation does not necessarily lead to higher soil carbon stocks (Poeplau et al. 2011). A Norwegian study conducted on partially afforested grazed grasslands found that even 50 years after planting, afforestation did not result in higher carbon sequestration than in the grassland (Strand et al. 2020).

6 Research needs

According to the reporting guidelines of the United Nations Framework Convention on Climate Change (UNFCCC), national inventories covering emissions and removals of GHGs from agriculture, forestry, and other land use (volume 4) should cover livestock and manure management (chapter 10) as well as carbon sequestration in grassland (chapter 6) (IPCC 2006). However, only grasslands classified as "managed land" by being fertilized, tilled, and sown are included in the national inventory reports, excluding semi-natural grasslands, even though these must be grazed or mown to be maintained. This presents a problem as semi-natural grasslands cover vast areas and may store large amounts of soil carbon. Yet grazing ruminants are classified as only contributing to GHG emissions, due to the lack of knowledge of soil carbon sequestration in grasslands, especially semi-natural grasslands. To enhance the knowledge basis for climate policy, more research is needed on grassland soil carbon, paying attention to regional differences in the complex interactions of grassland ecology and agricultural practices.

In a global perspective, it is especially important to acquire more knowledge on soil carbon in semi-natural grasslands, as attention has been drawn to grazing when the United Nations declared 2026 as the International Year of Rangelands and Pastoralists (United Nations 2022). It was then emphasized that keeping the vast areas of rangelands, with their large soil carbon sinks, managed under sustainable grazing practices, is essential for climate change mitigation (United Nations 2022).

Several measurement challenges exist when it comes to grassland soil carbon sequestration. One of these challenges is the spatial variability of soil carbon stocks. To effectively implement policies aimed at increasing soil organic carbon at a large scale and integrating soil organic carbon into national and international climate reporting, a combination of direct measurements and modeling is necessary (Smith et al. 2019). Standard protocols for measuring and monitoring soil carbon stocks would also facilitate comparisons between countries, regions, and land use types. However, it is essential to consider differences in climatic, ecological, and agricultural conditions when making such comparisons.

Assessing the soil carbon sequestration potential of grasslands is challenging due to the complexity of interactions between various factors such as vegetation characteristics, belowground biodiversity, grazing intensity, and management (Teague and Kreuter 2020).

Nonetheless, it is essential to gain more knowledge about the climate mitigation potential of grasslands, particularly semi-natural grasslands, to enhance the knowledge base for climate policy. For instance, do semi-natural grasslands have larger carbon stocks in deeper layers than cultivated grasslands? Can their management be optimized to increase carbon sequestration while maintaining their biodiversity? According to Janzen (2006), a better understanding of carbon flows in the soil and of the roles of soil microbes and fauna is necessary to balance the different ecosystem services expected from grasslands. It is particularly crucial to balance the need for carbon stabilization in the soil (i.e., climate mitigation) with the need for recirculation of dead organic matter to release nutrients to support plant growth (Janzen 2006).

7 Conclusion

We must take a fresh approach to climate policy and consider the potential of grasslands as vital carbon sinks. It is essential to focus on finding a balance between policies for climate mitigation and biodiversity management as the loss of biodiversity is as great a threat as climate change (IPBES 2019). Semi-natural grasslands are particularly important for biodiversity in Europe, and in some regions, they also contribute to food production and food security. Therefore, it is crucial to assess the multiple functions of grasslands, especially semi-natural grasslands, to optimize policy measures across sectors. To achieve this, more research is required to understand the potential of carbon sequestration in grasslands, particularly semi-natural grasslands, in different regions, so we can manage them optimally for climate mitigation and preservation of biodiversity, as well as other critical ecosystem services.

Acknowledgements The authors thank the Research Council of Norway (RCN) for financial support for the project CLIMATE-LAND (RCN-235560), and the work of Iulie Aslaksen received additional support from PLATON (RCN-295789).

Funding Open access funding provided by Statistics Norway

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