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Afforestation on Nordic grasslands: Trade-offs and synergies for climate mitigation, biodiversity, and ecosystem services

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ABSTRACT

Afforestation of abandoned grasslands has been proposed as a global climate mitigation strategy, but the climate benefits of tree planting on grasslands remain contentious. Studies worldwide indicate that grassland soils have large potential for carbon storage, while semi-natural grasslands often support high biodiversity and provide multiple ecosystem services, including grazing resources, pollinator habitats, and aesthetic landscape values. In boreal and alpine regions of the Nordic countries, grasslands sustain extensive low intensity farming, contributing to milk and meat production and enhancing food self-sufficiency. Evaluating the impact of afforestation on climate mitigation requires a comprehensive assessment that, in addition to the carbon balance, considers both geophysical forcing (such as albedo and evapotranspiration) and the broader landscape-level effects on biodiversity in displaced ecosystems. The article postulates for policy to be inclusive of both biodiversity preservation and climate change mitigation. Such an approach should be grounded in evidence-based assessments of the ecological and climate-related impacts of afforestation on the biodiversity of semi-natural grasslands.

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Introduction

The goals of the Paris Agreement on climate change (UNFCCC, 2015) and the Global Biodiversity Framework (CBD, 2022) are often overlapping, not at least as climate change is a large driver of biodiversity loss, and synergies in policy approaches are found e.g. in protecting and restoring wetlands and natural forests. Yet sometimes two goals are conflicting, as when climate mitigation involves land use change that may exacerbate loss of habitats important for biodiversity. Achieving climate goals requires carbon capture, with potential land use conflicts that may impair the biodiversity goals that emphasize the preservation, maintenance, and restoration of species-rich habitats. Afforestation, intending to increase ecosystem carbon sequestration and storage, is a component of the EU Green Deal (European Commission, 2019). In this article, we discuss these conflicting objectives, in the context of afforestation on ***abandoned*** semi-natural grasslands, which are grasslands no longer maintained by traditional management practices that preserve their characteristic biodiversity. Here, ***afforestation*** refers to denote policy-driven tree planting in semi-natural ecosystems (as opposed to recently deforested areas) aimed at carbon sequestration. In this context, afforestation adds further pressure on the unique and vulnerable biodiversity of semi-natural grasslands, which are already threatened by forest ***encroachment,*** defined as the increase in the abundance of (native) woody plants. In the context of Nordic semi-natural grasslands, encroachment occurs after ***abandonment*** of traditional management practices, such as grazing or hay mowing.

Afforestation on grasslands is a suggested climate mitigation action worldwide (Doelman et al., 2019), as trees capture carbon in biomass at higher rates than grasslands. Fast-growing coniferous trees, such as spruce, are often chosen (Bastin et al., 2019, 2020). However, afforestation can degrade the original open ecosystem (Parr et al., 2024) and must be evaluated against existing belowground carbon storage in the grasslands (Wieczorkowski and Lehmann, 2022, Veldman et al., 2019, Seddon et al., 2020). In many cases, afforestation may convert species-rich semi-natural ecosystems into monocultural production forests (Parr et al., 2024), more easily monitored and verified for carbon absorption (Stanley, 2024, Veldman et al., 2015). However, a single-factor (carbon) commodification of ecosystems is warned against (IPBES et al., 2022). Data-based, multiple-factor assessments for land management choices need to be encouraged, in contrast to a single-factor approach. Moreover, it is important to raise awareness of the socio-economic context behind the push for afforestation, as it is fundamentally connected to economy and politics (Hickel, 2018). Afforestation as land conversion results in loss of semi-natural and "wild areas" of natural ecosystems (Ellis et al., 2010).

Climate change and biodiversity loss are interconnected global crises, yet climate change has received more policy attention (Burrascano et al., 2016, Legagneux et al., 2018, Luyssaert et al., 2018, Ward et al., 2014). Both crises are deeply rooted in increasing resource extraction. An update of the planetary boundaries framework finds that six of the nine boundaries have been surpassed (Richardson et al., 2023). The UN Biodiversity Conference (COP 15) (CBD, 2022) highlighted the role of biodiversity in mitigating climate change. The Intergovernmental Panel of Biodiversity and Ecosystem Services (IPBES, 2022) warned against decision-making based on narrow sets of values, which prioritize market values of nature. Afforestation on abandoned grasslands is an example, with carbon treated as market commodity. To fulfill global goals of restoring and protecting at least 30 % of ecosystem areas (CBD, 2022), extensive management of semi-natural land is required. We suggest that strategies for afforestation on abandoned semi-natural grasslands are reconsidered and aligned with strategies for restoring semi-natural grasslands (by clearing forest encroachment and resuming continued extensive management).

This article draws on the scientific cooperation established through the Nordic research project (CLIMATE-LAND), which explores the trade-offs and synergies between biodiversity and climate mitigation in relation to proposed afforestation on abandoned semi-natural grasslands. The CLIMATE-LAND project included pilot studies in Iceland and Norway (Fig. 1) and facilitated broad discussion on future research needs, highlighting the ecological value of grassland and their potential role in balancing climate mitigation with biodiversity conservation. Grasslands' biodiversity varies significantly, based on hydrology, soil abiotic and biotic properties, and current and historical management (Lindborg et al., 2008). It is crucial to account for these regional differences when aligning land use strategies with multiple environmental goals, with a particular focus on Nordic semi-natural grasslands in this study.

In the Nordic countries, semi-natural grasslands comprise both lowland and alpine (above the tree line) grasslands, with former hay meadows and pastures grazed by sheep, cattle, reindeer, and other grazers. In boreal and alpine grasslands, there is summer farming and/or rangeland grazing. Unless managed by grazing, or other traditional practices, semi-natural grasslands are subject to encroachment by forest (below the tree line) or shrub (above the tree line). Current tree lines are rising with warming climate, however, above the tree line, afforestation is (by definition) impossible, and the proposed afforestation is on semi-natural grasslands below the tree line.

There are relatively few studies of the soil carbon potential of Nordic semi-natural grasslands, and moreover, few of these studies take a comprehensive approach to both climate mitigation, biodiversity, food security, and other ecosystem services of the semi-natural grasslands (Rasse et al., 2019). We aim to explore how these aspects are interrelated as background to a policy proposal inclusive of both the unique biodiversity and the carbon storage potential of semi-natural grasslands.

Nordic semi-natural grasslands: biodiversity, current status, and challenges

Semi-natural grasslands are transitional ecosystems maintained in an open successional stage by management practices such as grazing, hay mowing, or fire (Scasta et al., 2016, Norderhaug et al., 1999). These ecosystems can only survive if extensive (i.e. low intensity) land use is upheld (Fig. 2). The European semi-natural grasslands have resulted from a long history of extensive land use, originating in the Neolithic period (Dengler et al., 2014). They often possess high biodiversity (Dengler et al., 2014, Emanuelsson et al., 2024). Some semi-dry, base-rich semi-natural grasslands in Europe hold the world record for vascular plant-richness on a small scale (Wilson et al., 2012), and also support high diversity in associated groups of animals, such as insect pollinators (Öckinger and Smith, 2007, Ekroos et al., 2013). Many plant species associated with semi-natural grasslands originated in natural grasslands (Dengler et al., 2014). Most European plant species occur on sunny or half-shady microhabitats (Ellenberg et al., 1991). The unique biodiversity of semi-natural grasslands is often explained by grazing and hay mowing, leading to reduced competition for light, reduced build-up of biomass, a more open landscape (by preventing encroachment of shrubs and trees), and low soil nutrient (N and P) levels (Pykälä 2005). Although the extent of openness in past European landscapes is debated, Pearce et al. (2023) argue that, before anthropogenic impacts, large herbivores maintained the open landscapes without dense forests. Pearce et al. (2023) warn against nature restoration by tree planting since increased shading and soil acidity may create unfavorable conditions for biodiversity developed in heterogeneous landscapes.

In the Nordic countries, the area of semi-natural grasslands has significantly decreased over the last century due to the intensification of agriculture, land development, and abandonment of grazing and other traditional practices (Aune et al., 2018), resulting in habitat loss and loss of biodiversity (Emanuelsson et al., 2009). Red lists of endangered plants, fungi, insects, birds, and other groups of organisms document the status of species depending on semi-natural ecosystems. In Norway, 29 % of the threatened species depend on these ecosystems (Norwegian Biodiversity Information Centre, 2021). In Sweden, semi-natural habitats are critical for 34 % of the red-listed species (SLU Swedish Species Information Centre, 2020) and in Finland for 24 % (Finland's Environmental Administration, 2019). Afforestation results in the loss of grassland habitats, with a low likelihood or slow rate of recovery (Buisson et al., 2022). Plant species may persist long after abandonment, implying a potential for grassland restoration by resumed traditional management. However, persistence time is shorter after afforestation due to abrupt and large changes in vegetation, soil conditions, and loss of light (Lennartsson, 2016).

A pilot study of the CLIMATE-LAND project explored biodiversity and conditions for biodiversity at three study sites in Norway (Fig. 1) with different grazing pressures (Emanuelsson et al., 2024). Biodiversity was highest in the semi-natural grassland with moderate grazing pressure, lower with light grazing pressure, and the lowest in the abandoned semi-natural grassland. Conditions for biodiversity were studied at landscape level, comparing the semi-natural grassland with planted coniferous forest landscapes and abandoned pasture landscapes. The results showed that conditions for biodiversity were best in the landscapes with semi-natural grassland and worst in the landscapes with planted coniferous forests (Emanuelsson et al., 2024).

Nordic semi-natural grasslands: carbon

Grasslands store approximately one-third of global terrestrial carbon stocks (Bai and Cotrufo, 2022). A key question is whether management for biodiversity, by grazing, may also maintain already stored and potentially increase soil carbon, and how large this benefit might be compared to the potential climate benefit of afforestation. Evidence is contrasting, depending on regional differences, and there are large uncertainties in long term effects on soil carbon under land use change

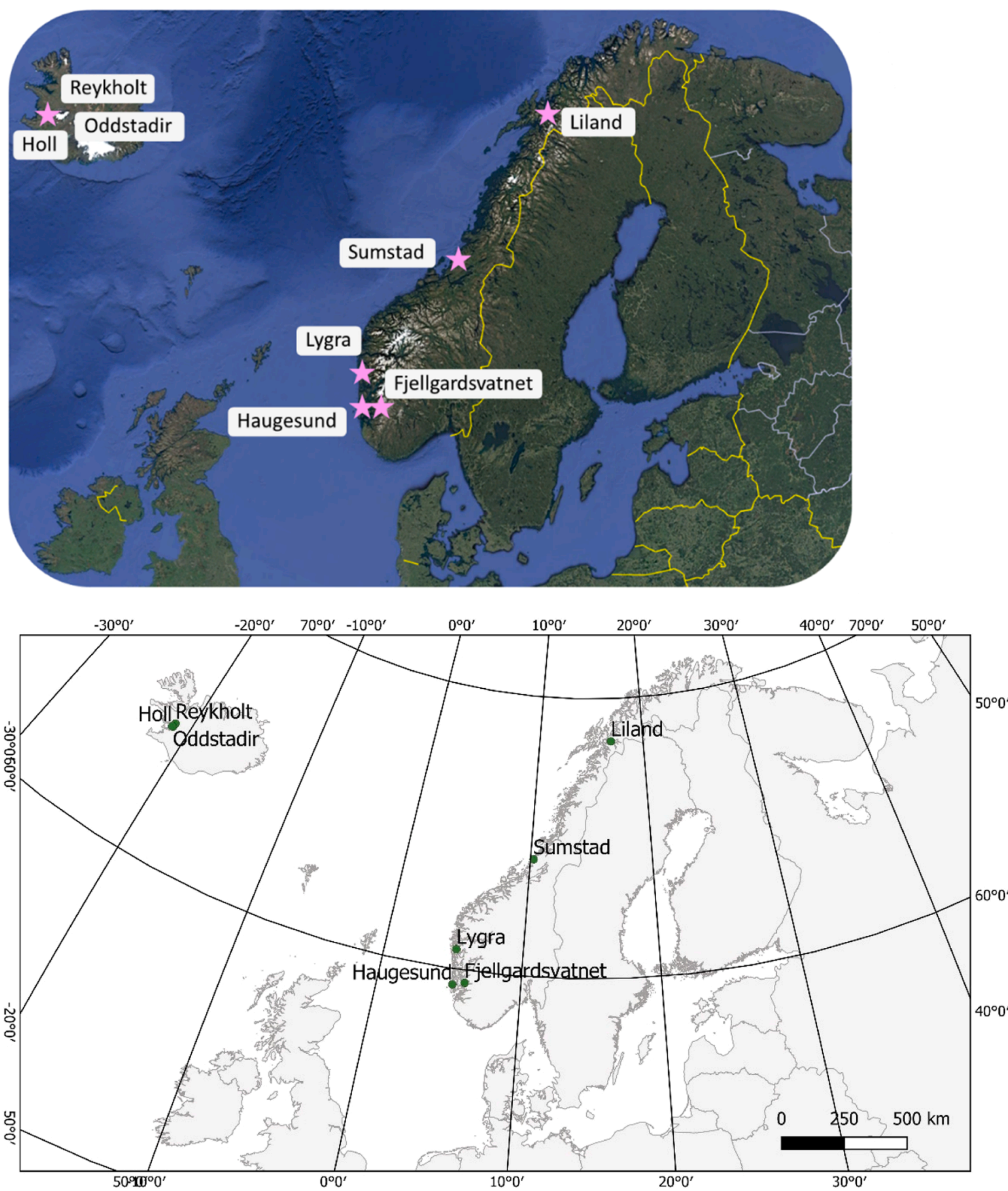

Fig. 1. Pilot study sites of semi-natural grasslands in Iceland and Norway in the CLIMATE-LAND project. The project examined carbon balance at three study sites in Iceland (Thorhallsdottir and Gudmundsson, 2023) and biodiversity and environmental conditions at three study sites (and two supplementary areas) in Norway (Emanuelsson et al. 2024), each site subjected to varying levels of grazing pressure.

(Fig. 2). The potential for increased soil carbon in semi-natural grazing land is uncertain, especially in mountain grasslands (De Wit et al. (2015), yet studies point out that, in general, there are substantial effects of grazing and of forest expansion on vegetation dynamics that affect the soil carbon potential (Rasse et al., 2019). More knowledge is needed on the interaction of grazing, soil carbon, and other grassland ecosystem services (Austrheim et al., 2016), and whether soil carbon sequestration in grazing land can offset methane emissions from ruminants and how the effect of grazing on vegetation can affect albedo of grassland.

Although there is lack of evidence on soil carbon in Nordic semi-natural grasslands, several studies have explored effects of grazing, especially in mountain grazing areas, and estimated soil carbon in semi-natural grazing land in Norway and how it is impacted by grazing intensity. In a sheep grazing mountain area, Speed et al. (2014) estimated soil organic carbon to about 13 kg/m^2 for high grazing intensity (soil depth 22 cm) and about 21 kg/m^2 for long-term (50 years) grazing exclusion (soil depth 29 cm), but the difference was not significant, and carbon pools were more influenced by soil type than by sheep exclusion. In another mountain area in Norway, with drier climate, Martinsen et al. (2011) found that seven year of high grazing pressure reduced soil organic carbon stocks compared to non-grazed areas, while moderate grazing pressure increased the soil organic carbon stock. Soil carbon was estimated to about 7.9 kg/m^2 (sum of O-horizon, mean depth 8.4 cm and mineral horizon, mean depth 17.8 cm) (Martinsen, 2011).This is comparable to estimates for soil carbon in European mountain grassland, reported to 8–10 kg/m^2 (to 30 cm depth) Sjögersten et al., (2011)), for tundra and boreal forest about 18 kg/m^2 and 12.5 kg/m^2 respectively (to 3 m depth) (Jobbagy and Jackson, 2000). For comparison, soil carbon in forest in Norway was estimated to 10.2–31.3 kg/m^2 (soil depth 32–70 cm and some profiles to 1 m depth) (Strand et al., 2016), with large variation between soil types, and average soil carbon stocks for cultivated land in Norway were estimated to 15.5 kg/m^2 (to maximum 1 m depth) (Rasse 2019). The studies of grazing on semi-natural mountain grasslands in Norway indicated that the effects on soil carbon vary considerably and are sensitive to environmental and climatic factors, and the estimates were both higher and lower than the average for European mountain grasslands, as well as the average for forest in Norway (summarized in Table 1). This variation across sites underlines the need for carrying out large-scale studies of soil carbon in Nordic semi-natural grasslands to obtain results that are applicable for climate change mitigation strategies.

Grazing intensity is found to be a key factor for effects on soil carbon. It is crucial to distinguish between semi-natural and intensively managed grasslands. Intensively managed grasslands – and cropland - do not retain soil organic carbon to the same extent as semi-natural grasslands, although this varies depending on climate, soil type, and management practices (Lindborg et al., 2023). Lindborg et al. (2023) argue that soil carbon storage may be higher in semi-natural grasslands, especially those with trees (wood pastures), compared to agronomically improved grasslands. Martinsen et al. (2011) point out that small changes in grazing pressure can have an effect on soil carbon, and that a grazing pressure adapted to the productivity of the ecosystem can stimulate plant growth and thus increase the amount of soil carbon. These studies, highlighting the importance of grazing intensity, point to the need for enhanced knowledge synthesis for supporting climate change mitigation strategies aligned with agricultural practices.

New data from Iceland shed light on the effects of grazing management and, moreover, the importance of continuity of grazing over time. A pilot study of the CLIMATE-LAND project explored soil carbon fluxes and stocks in semi-natural grasslands in Iceland and found higher CO_2 uptake on grazed sites compared to non-grazed sites that were otherwise similar (Thorhallsdottir and Gudmundsson, 2023). The annual change over 50 years in soil carbon stock was 0.14 kgC/m^2 and 0.07 kgC/m^2 for grazed sites and non-grazed sites, respectively (Thorhallsdottir and

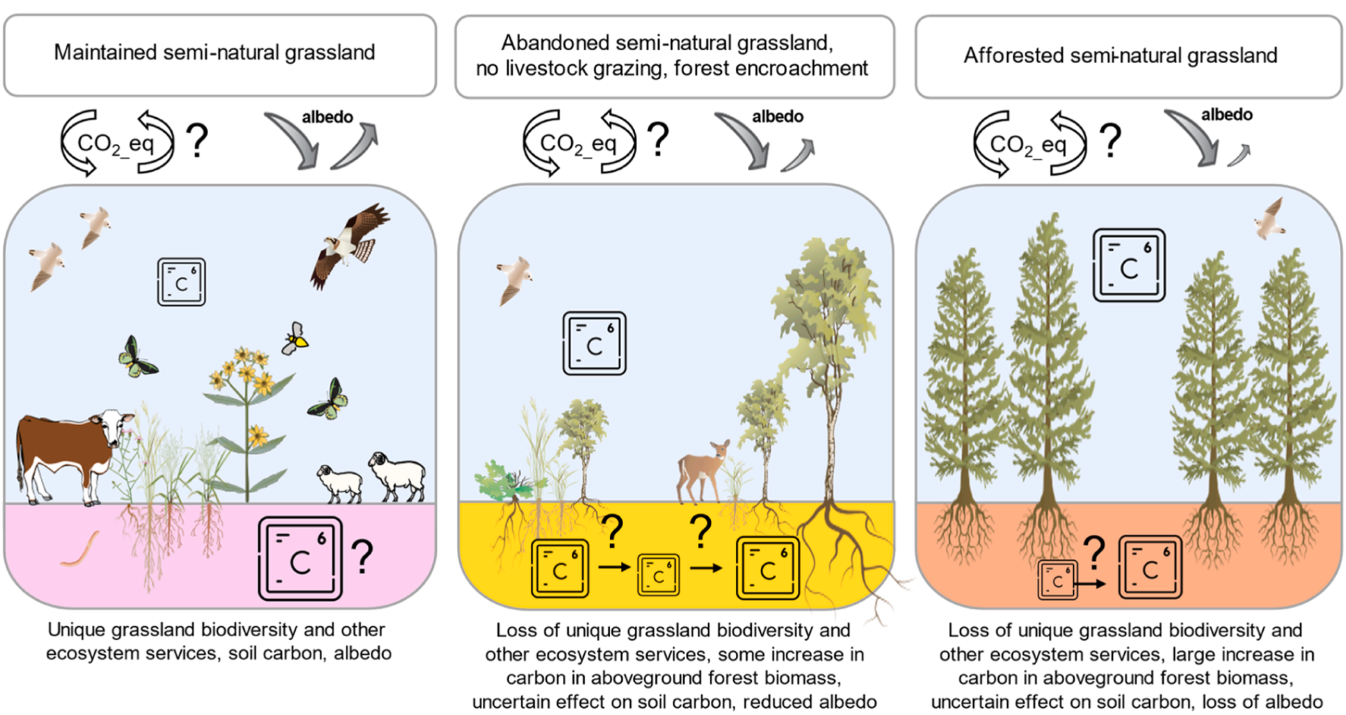

Fig. 2. A schematic overview illustrating the discussion of trade-offs and potential synergies related to the climate change mitigation potential, biodiversity maintenance and loss, and other ecosystem services in three stages of the semi-natural grasslands, i.e. maintained, abandoned and afforested. The comparison of climate mitigation potential across the land use alternatives has focus on effects on soil carbon and albedo, and the effects on the atmospheric exchange of greenhouse gas balances, in terms of CO_2-equivalents, are not further hypothesized. With forest encroachment, there is loss of unique grassland biodiversity and other ecosystem services, possibly loss of soil carbon, although increasing soil carbon over time, and reduced albedo. With afforestation, carbon in aboveground forest biomass increases, while there is loss of soil carbon after tree planting and increasing soil carbon over time, loss of unique grassland biodiversity and other ecosystem services, and loss of albedo.

Table 1
Overview of soil carbon estimates comparing grazing land to other ecosystems.

Ecosystem	Soil carbon	Soil depth	Comment	Source
Mountain grazing land - Norway High grazing intensity	13 kg/m^2	22 cm	No significant difference high intensity and grazing exclusion	Speed et al. (2014)
Mountain grazing land - Norway Long term grazing exclusion	21 kg/m^2	29 cm	No significant difference high intensity and grazing exclusion	Speed et al. (2014)
Mountain grazing land - Norway	7.9 kg/m^2	Sum O-horizon (mean 8.4 cm) and mineral horizon (mean 17.8 cm)	Drier climate	Martinsen et al. (2011)
Mountain grasslands - Europe	8–10 kg/m^2	30 cm		Sjögersten et al. (2011)
Tundra - regional average	18 kg/m^2	to 3 m		Jobbagy and Jackson (2000)
Boreal forest - regional average	12.5 kg/m^2	to 3 m		Jobbagy and Jackson (2000)
Boreal forest - Norway	10.2–31.3 kg/m^2	32–70 cm, some profiles to 1 m		Strand et al. (2016)
Cultivated land - Norway	15.5 kg/m^2	to maximum 1 m		Rasse (2019)

Gudmundsson, 2023). These numbers are of the same order of magnitude as land-use-related factors applied in greenhouse gas reporting for Iceland to the UNFCCC and the Kyoto Protocol (Keller et al., 2019). The grazed sites also had higher soil organic carbon levels, indicating that grazing can contribute to increase or maintain soil organic carbon. The results indicate a considerable reduction in soil organic carbon when grazing is discontinued. Net ecosystem exchange over the growing season is 3.72 tCO_2/hectare and 2.16 tCO_2/hectare for grazed sites and non-grazed sites, respectively, thus grazing seems to nearly double carbon sequestration per unit area (Thorhallsdottir and Gudmundsson, 2023). This study demonstrates the importance of a known timeline for land use on the study sites and the long continuity of grazing, reflected in the soil. Ongoing studies in Iceland, comparing 38 semi-natural grazed sites with parallel long-term non-grazed sites, confirm the findings of Thorhallsdottir and Gudmundsson (2023) and indicate that grazing intensity is an important factor influencing soil carbon content (Thorhallsdottir, unpublished data).

Other studies also found that grazing intensity significantly affects soil organic carbon content. A global meta-study (based on 287 publications) of effects on soil organic carbon of grazing intensities, found that light grazing intensity significantly increased soil organic carbon (to 10 cm), while heavy and moderate grazing intensity reduced soil organic carbon (Lai and Kumar, 2020). Grazing intensity was not uniformly defined in the meta-study, as the grazing intensities (light, moderate and heavy) were defined by each publication, with different criteria, including the number of grazing animals per unit of area, as well as environmental factors, defining grazing intensity differently in different grazing lands (Lai and Kumar, 2020). In a study of grazing exclusion, Roy and Bagchi (2022) found that grazing lead to increased soil carbon and refer to empirical estimates from around the world indicating that moderate grazing intensity can increase soil carbon, compared to grazing exclusion. The results of Roy and Bagchi (2022) indicate a linkage between herbivores and soil microbes that can lengthen the residence time for soil carbon, and they point to the study by Lundgren et al. (2020) that the influence of herbivores on grazing ecosystems may be of high importance for soil carbon continuing to provide climate change mitigation.

Considering belowground biota and processes is important for improved assessments of the climate mitigation benefits of maintaining semi-natural grasslands versus afforestation on abandoned semi-natural grasslands. It has become clear that the mycorrhizal associations of the vegetation are closely related to soil nutrient cycling and carbon storage across ecosystem types and biomes (Read and Perez-Moreno, 2003, Steidinger et al., 2019). Grassland vegetation typically forms arbuscular mycorrhiza, while most boreal and subarctic trees form ectomycorrhiza. Thus, any vegetation change will also involve immediate shifts in mycorrhizal fungal communities. These mycorrhizal types are formed by species-rich fungal communities that associate with plant roots and possess contrasting mycelial growth patterns and capacities to decompose and mobilize nutrients from the soil (Smith and Read, 2008). A study in a Norwegian mountain area compared carbon pools in a grassland, an *Empetrum*-dominated heath and a *Salix*-shrub community and found that grasslands had the largest total ecosystem carbon pool as compared to the other vegetation types (Sørensen et al., 2018). The total ecosystem carbon pool in the semi-natural grassland was twice that of the shrub community due to more soil organic carbon. The heath community stored one and a half times more carbon than the shrub community. The large difference in carbon pools in the three habitats indicate that shrub-dominated areas may be draining the carbon-rich alpine soils because of high rates of decomposition (Sørensen et al., 2018). Other studies also suggest that soil carbon could be lost with forest expansion into previously unforested mountain ecosystems, likely due to a parallel shift in belowground biota (Clemmensen et al., 2021, Tonjer et al., 2021). Overall, afforestation of grasslands (and heathlands) would promote ectomycorrhizal fungi at the expense of arbuscular (and ericoid) mycorrhizal fungi, which will likely lead to soil carbon loss due to accelerated decomposition of soil organic matter in the presence of trees and mycorrhiza fungi (Parker et al., 2021, Tonjer et al., 2021, Clemmensen et al., 2021, Castano et al., 2022). The association of grassland plants with arbuscular mycorrhizal fungi likely has a positive long-term effect on grassland soil carbon stocks through mycelial growth, particularly in the subsoil (Sosa-Hernández et al., 2019). To summarize the evidence, the issue is to what extent the carbon gains from aboveground biomass growth, often the main motivation for afforestation, can offset the soil carbon loss due to changes in mycorrhizal communities resulting from afforestation. The evidence indicates that this is only partly true, as trees only partly compensate for the soil carbon loss from afforestation, and it takes time before forest soil carbon is built up (Strand et al., 2021). However, if the reduced albedo is considered, there may be loss of climate mitigation potential from afforestation, and moreover, afforestation has a high cost in terms of loss of unique biodiversity (Fig. 2).

Afforestation as climate policy: soil carbon, albedo, and biodiversity

In Norway, afforestation was implemented as a climate policy measure in a pilot phase (Norwegian Environment Agency et al., 2013). Afforestation was proposed for abandoned grasslands, defined as open areas no longer under traditional management, i.e., areas under forest encroachment that do not yet meet the forest definition (10 per cent canopy cover) (Norwegian Environment Agency et al., 2013). Typically, abandoned semi-natural grassland in Nordic (boreal) regions undergo succession to deciduous forest and further on to coniferous forest. An aspect of the afforestation policy involved replacing deciduous forest with coniferous trees.

In global studies, evidence is contrasting on the effect of afforestation on soil carbon of semi-natural grasslands. Mayer et al. (2020) reviewed meta-analyses at regional and global scales and found that while afforestation on cropland may result in a significant increase in soil carbon, in contrast, afforestation of grasslands, soil carbon may in general remain unchanged or decrease. Poeplau et al. (2011) found that 75 % of grassland-to-forest conversions showed soil carbon loss, even after 100 years. Stocks of soil carbon differ under different tree species, with coniferous species accumulating more carbon in the forest floor and broadleaved species tending to store more carbon in the mineral soil.

For Nordic semi-natural grasslands, evidence on effects of afforestation on soil carbon is limited. We lack studies from Nordic environmental conditions and can only to some extent infer from international studies as effects on soil carbon are context-specific, depending both on environmental condition and management regimes, that typically show great variations in Nordic countries, spanning wide gradients of topography. Summarizing the effects of the pilot afforestation in Norway, drawing on several studies from Norway, Søgaard et al. (2023) concluded that the impact of afforestation on soil carbon in abandoned grazing land is not straightforward, and may potentially have a negative effect on soil carbon. Moreover, the finding that afforestation on grazing land may reduce soil carbon stocks is supported by a meta-study of effects on soil carbon of afforestation in Northern Europe (Bárcena et al., 2014). This result is consistent with the standard methodology used in the national greenhouse gas emission inventory report under UNFCCC (Norwegian Environment Agency et al., 2022), which indicates that converting grazing land to forest results in a loss of soil carbon (Søgaard et al., 2023). However, the effects on soil carbon of afforestation on grazing land can vary considerably between sites, depending on soil conditions and environmental factors. An example is a study of afforestation in Mid-Norway, by Strand et al. (2021), with a 50-year-old plantation of Norway spruce (*Picea abies* L.) on former pasture land. Their hypothesis was that the afforested site had reached a higher soil carbon stock than the adjacent pasture site. Since no soil measurements were taken 50 years ago, the effect of afforestation was explored by a "space-for-time" approach, with the study site selected on a farmland where part of the area was converted from agricultural use to plantation forest. The study found no significant difference in soil carbon (down to 30 cm between the grassland and the afforested site, 50 years after planting. Moreover, soil carbon stocks in the afforested plantation were not significantly different from those in a nearby 80-year-old forested area - suggesting that the potential for further increasing soil carbon stocks in the upper 30 cm of the soil by afforestation is not large. The study was done on fine-textured soil, and the agricultural site had high bulk density, presumably from soil compaction from grazing cattle. Thus, the similar soil carbon stocks in agricultural site and forest stands might in part be a consequence of high soil compaction and lower soil organic matter content in the agricultural site compared with the forest. Although forest sequesters more carbon aboveground compared to pasture, it is highly unlikely that forest planting on fine-textured soils will lead to any significant increase in stable soil carbon. This should be taken into account in the discussions of trade-offs of afforestation in a climate perspective, where carbon sequestration must be balanced against values of other ecosystem services (Strand et al., 2021).

The climate mitigation potential of afforestation strongly depends on the forest harvest management. For afforestation as a climate policy, it is suggested that the plantation forests are harvested after about 70 years to initiate a new growth cycle and maintain high growth-rates and sequestration rates. The large uncertainty in estimates of the carbon balance recovery time after forest clear-cutting is emphasized by Peichl et al. (2023). Increased carbon storage may be a result in the short term while trees are growing (Kauppi et al., 2022). However, the long-term effects on climate mitigation are questioned (Peng et al., 2023). Forest harvesting generally reduces soil carbon stocks, most evidently in the organic horizon, although there are indications of losses in deeper soil layers (60–100 + cm) (Mayer et al., 2020), and it takes several decades for soil carbon to recover (James and Harrison, 2016). In the boreal forests of Fennoscandia, coniferous forests typically mature within 70–120 years, with large areas harvested in a 70–100-year rotation cycle (Määttänen et al., 2022). In Norway, forests are often harvested before reaching mature age, resulting in reduced carbon uptake (Belbo and Granhus, 2023), thereby creating a carbon debt (Holtsmark, 2012). A recent study, based on the Norwegian national forest inventory, finds that old boreal forests, more than 100 years older than recommended rotation length, continue to sequester carbon for several decades and maintain carbon in biomass and soil better than previously assumed (Stokland, 2021). Thus, old forests contribute more to climate mitigation than generally assumed, a result that points to the importance of managing existing natural forests for climate mitigation and other ecosystem services provided by forests, in contrast to afforestation with plantation forest and cutting in a 70-years cycle. Stokland (2021) emphasizes that from a climate mitigation perspective, it seems a good strategy to extend the rotation length beyond what is currently recommended (assuming that the old forest stand density is satisfactory). Presumably, old, originally planted forests would show the same pattern of carbon accumulation as found by Stokland (2021). However, the policy of afforestation with plantation forest assumes that such plantations are cut in the standard rotation cycle. The result that old forests contribute more to climate mitigation than generally assumed, points to the importance of managing existing natural forests for climate mitigation and other ecosystems provided by forests, in contrast to afforestation for climate purpose, with the condition to plant new forest and cut in a 70-years cycle (or before). Moreover, single-species plantation forest may have weaker conditions for reaching old age since they may be more exposed to storm damage and insect pests than multi-species forests with age-diverse stands. There is also less plant biodiversity (Skarpaas, og Halvorsen, 2022) in planted forest stands and less plant biodiversity in coniferous planted stands as compared to birch forest (Kjønaas et al., 2021).

Besides greenhouse gas balances, afforestation as a climate policy must consider the influences on the geophysical components of the energy budget (Bonan, 2008). For example, afforestation of grassland decreases albedo, which is the proportion of solar radiation reflected from the land surface back to the atmosphere. Tree cover often absorbs more solar radiation than other land covers, due to darker surface and less snow, thus partially counteracting the mitigation effect of afforestation. While Mooney et al. (2020) suggested that albedo impacts cannot definitively support or dismiss afforestation as a climate mitigation policy, changes in albedo are considered a significant concern for mitigation efforts in the boreal region (Griscom et al., 2017, Hasler et al., 2024, Lawrence et al., 2022). The importance of herbivores to reduce the abundance of shrubs and maintain higher albedo is emphasized by Olofsson and Post (2018) in their study of Arctic tundra. A study on the expansion of mountain birch forest in Norway found that the reduced albedo - when forest replaced open grasslands in mountain areas, snow-covered in winter - outweighed the increase in carbon uptake from forest expansion, leading to a net warming effect of birch expansion (De Wit et al., 2014). On the other hand, substitution of coniferous forest with birch forest by active forest management resulted in substantial cooling compared to expansion of coniferous forest, since birch forest has higher albedo than coniferous forest, especially during winter (Bright et al., 2014). Thus, forest encroachment of open areas will lead to climate warming while replacement of coniferous stands with birch would lead to cooling.

Summarizing the evidence on climate change mitigation potential, climate policy should prioritize enhancing carbon sequestration in areas best suited to environmental conditions while also considering regional and local perspectives to identify suitable areas. Integrated policy approaches and public acceptance are key in ensuring the effectiveness of such strategies. In this context, public opinion on conservation and environmental policy is particularly important, especially in contested issues like afforestation. Simply providing more information available does not guarantee that policy makers will make scientifically informed decisions (Kahan, 2010). However, the legitimacy of conservation policies often hinges on the public support and exploring people's preferences and the factors shaping their views, is essential for effective communication and policy design (Kahan, 2010).

Considering the climate policy options, it is crucial to gain insight into the public support for climate policies that are affecting the environment and biodiversity. Official surveys, such as the EU survey Eurobarometer on environmental attitudes, and the People and Nature Surveys for England, conducted by the UK's Department for Environment, Food & Rural Affairs and Natural England, provide valuable insights into public preferences. Peoples' preference for landscapes, in particular, offer useful information for shaping policies on climate and biodiversity. In the CLIMATE-LAND project, a choice experiment survey conducted with a representative sample of the population in Norway examined public preferences regarding afforestation and the restoration of abandoned semi-natural grasslands. The survey revealed strong support for strategies that integrate climate mitigation with biodiversity conservation (Iversen et al., 2021). Respondents evaluated different scenarios, considering the impacts of afforestation and grassland restoration on landscape aesthetics, biodiversity conservation, and climate mitigation efforts. Two scenarios stood out as particularly popular: one where 50 % of abandoned semi-natural grasslands are restored to protect biodiversity, and another where 50 % are restored while 25 % are afforested. The results underscore support for balancing biodiversity protection with afforestation efforts, highlighting the importance of landscape and biodiversity values in shaping policies that aim to achieve multiple objectives (Iversen et al., 2021). The preference for the second scenario, where twice as much land is restored as is afforested, suggests a public inclination toward restoration, two units of grassland for every one unit afforested. As pointed out by Kahan (2010), in the communication from science to policy, to ensure a legitimate policy on nature conservation, it is vital to ask questions about people's preferences.

Nordic semi-natural grasslands: food self-sufficiency

Species-rich semi-natural grasslands provide multiple ecosystem services, including grazing resources, habitats for pollinators and *in situ* conservation of genetic resources from wild relatives of domesticated plants (Bengtsson et al., 2019, Bratli et al., 2012). In Nordic and other countries where crop cultivation is climatically constrained, livestock grazing of semi-natural grasslands, especially in the north and in alpine areas (rangeland), supports milk and meat production through extensive (low-intensity), rather than high-intensity, farming. A study initiated by Nordic Council of Ministers explored the potential for enhanced food self-sufficiency while at the same time meeting climate targets (Nordic Council of Ministers, 2017). They emphasized the importance of Nordic countries to utilize their natural potential for food production, given the climatic constraints, which calls for cultivating grain and vegetables on the arable land, and using semi-natural grasslands for grazing to obtain milk products and meat. The study found that especially in Norway which has only small areas of arable land, it is especially important to use the large areas of semi-natural grasslands land for grazing ruminants, to obtain better food self-sufficiency and contribute to a sustainable food future. The ruminants convert grass, that cannot be consumed by humans, into high-protein food for humans. Moreover, the grazing ruminants have an important role in maintaining open landscape and unique biodiversity (Nordic Council of Ministers, 2017).

Semi-natural grasslands provide food of high nutritional and gastronomic value (Bele et al., 2018), reflecting the landscape and cultural heritage (Bele et al., 2024). A study of grazing on semi-natural alpine grasslands used for summer farming in Norway found high levels of antioxidants in mountain plants, contributing to the high quality of milk produced from alpine ranges (Sickel et al., 2012). Economic incentives are needed to encourage multifunctional agriculture (Helfenstein et al., 2024), particularly targeting continued grazing of semi-natural grasslands (Ihse, 2017). In a pilot study of the CLIMATE-LAND project, Hillestad (2018) interviewed farmers in areas selected for afforestation in Norway and found that farmers preferred agricultural support for grazing rather than for afforestation. A Swedish study suggested that grazing in pasture-forest mosaics could be more profitable than forestry (Kumm and Hessle, 2020), by creating large grazing areas from wooded semi-natural pastures and previously grazed forests (Kumm and Hessle, 2023). Further, when comparing afforestation and grazing of semi-natural grasslands, it is important to differentiate between local, national, and global benefits in order to target the environmental, economic, and social aspects of the global Sustainable Development Goals. While grazing supports local and national food self-sufficiency, the benefits of afforestation may accrue to stakeholders involved in large-scale greenhouse gas emission accounting in the global carbon market (Kolinjivadi et al., 2019, Stanley, 2024).

Conclusions

Semi-natural grasslands, often targeted for afforestation, play an important role in storing soil carbon and should not be overlooked in climate policy decisions. Given their unique biodiversity and the threat of habitat loss, the impact of afforestation on these areas warrants careful consideration (Fig. 2). Policymakers must focus on the management of both alpine and lowland grasslands, where extensive management practices, such as grazing, are essential to sustaining these ecosystems. In weighing trade-offs involved in afforestation from a climate perspective, carbon sequestration must be balanced against other ecosystem services, such as biodiversity, the aesthetic value of open landscapes, and the livelihoods and food production from smallholder grazing on semi-natural grasslands.

To meet the obligations of the Global Biodiversity Framework (CBD, 2022), semi-natural grasslands must be preserved through extensive management practices, within agricultural landscapes. We recommend an inclusive policy approach, that integrates agricultural policies to preserve the unique biodiversity of semi-natural grasslands while also preserving their soil carbon stocks. A stronger knowledge base is needed to assess trade-offs and synergies in land use (Polasky et al., 2008) to achieve multiple environmental objectives (Olsson et al., 2012) within a cohesive framework of a "climate and nature cure" (Rusch et al., 2022). Here, accurate mapping of grassland ecosystems, accounting for management intensity, is essential to identify biodiversity hotspots and promote more diverse agricultural landscapes. This aligns with the recommendations of the international System of Environmental-Economic Accounting-Ecosystem Accounting (United Nations, 2021) and the Global Biodiversity Framework (CBD, 2022). The wide variation and uncertainty in soil carbon estimates, as well as the importance of factors such as albedo and evapotranspiration, illustrate the need for more knowledge. More research is needed to evaluate how management practices impact the soil carbon potential of Nordic semi-natural grasslands (Norderhaug et al., 2023), ensuring that policies for climate mitigation, biodiversity conservation, and other ecosystem services, including food self-sufficiency, are aligned effectively.

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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.

Data availability

No data was used for the research described in the article.

References

Aune, S., Bryn, A., Hovstad, K.A., 2018. Loss of semi-natural grassland in a boreal landscape: impacts of agricultural intensification and abandonment. J. Land Use Sci. 13, 375–390. https://doi.org/10.1080/1747423X.2018.1539779.

Austrheim, G., Speed, J.D.M., Evju, M., Hester, A., Holand, O., Loe, L.E., Martinsen, V., Mobaek, R., Mulder, J., Steen, H., Thompson, D.B.A., Mysterud, A., 2016. Synergies and trade-offs between ecosystem services in an alpine ecosystem grazed by sheep - an experimental approach. Basic Appl. Ecol. 17, 596–608.

Bai, Y., Cotrufo, F., 2022. Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science 377 (6606), 603–608. https://doi.org/10.1126/science.abo2380.

Bárcena, T.G., Kiaer, L.P., Vesterdal, L., Stefansdottir, H.M., Gundersen, P., Sigurdsson, B. D., 2014. Soil carbon stock change following afforestation in Northern Europe: a meta-analysis. Glob. Change Biol. 20, 2393–2405.

Bastin, J.-F., et al., 2019. The global tree restoration potential, 5 July 2019 Science 365 (6448), 76–79. https://doi.org/10.1126/science.aax0848.

Bastin, J.-F., et al., 2020. Erratum for the Report: "The global tree restoration potential" by J.-F. Bastin et al., and for the Technical Response "Response to Comments on 'The global tree restoration potential'" by J.-F. Bastin et al., 29 May 2020 Science 368, eabc8905. https://doi.org/10.1126/science.abc8905.

Belbo, H., Granhus, A., 2023. Årsaker til tidlig hogst: undersøkelser rettet mot skogeiere, virkeskjøpere og kommunal skogbruksmyndighet. NIBIO-rapport 9:149. Norwegian Institute of Bioeconomy Research (NIBIO).

Bele, B., Norderhaug, A., Sickel, H., 2018. Localized agri-food systems and biodiversity. Agriculture 8, 22. https://doi.org/10.3390/agriculture8020022.

Bele, B., Nielsen, V.K.S., Fairclough, G., et al., 2024. A heritage without boundaries: nature-culture synergies in and around norwegian protected landscapes. Hum. Ecol. https://doi.org/10.1007/s10745-023-00468-z.

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H.G., Lindborg, R., 2019. Grasslands—more important for ecosystem services than you might think. Ecosphere 10, e02582. https://doi.org/10.1002/ecs2.2582.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449. https://doi.org/10.1126/science.1155121.

Bratli, H., Jordal, J.B., Norderhaug, A., Svalheim, E., 2012. Naturfaglig grunnlag for handlingsplan naturbeitemark og hagemark. Bioforsk Rep. 7, 193. ⟨http://hdl.handle.net/11250/2447488⟩. Bioforsk: Ås, Norway.

Bright, R.M., et al., 2014. Climate change implications of shifting forest management strategy in a boreal forest ecosystem of Norway. Glob. Change Biol. 20, 607–621.

Buisson, E., Archibald, S., Fidelis, A., Suding, K.N., 2022. Ancient grasslands guide ambitious goals in grassland restoration. Science 377 (6606), 594–598. https://doi.org/10.1126/science.abo4605.

Burrascano, S., Chytr, M., Kuemmerle, T., Giarrizzo, E., Luyssaert, S., Sabatini, F.M., Blasi, C., 2016. Current European policies are unlikely to jointly foster carbon sequestration and protect biodiversity. Biol. Conserv. 201, 370–376.

Castano, C., Hallin, S., Egelkraut, D., Lindahl, B.D., Olofsson, J., Clemmensen, K.E., 2022. Contrasting plant-soil-microbial feedbacks stabilize vegetation types and uncouple topsoil C and N stocks across a subarctic-alpine landscape. N. Phytol. 238, 2621–2633. https://doi.org/10.1111/nph.18679.

CBD. 2022. The Kunming-Montreal Global Biodiversity Framework (GBF). Convention on Biological Diversity. ⟨https://www.cbd.int/gbf⟩.

Clemmensen, K.E., Durling, M.B., Michelsen, A., Hallin, S., Finlay, R.D., Lindahl, B.D., 2021. A tipping point in carbon storage when forest expands into tundra is related to mycorrhizal recycling of nitrogen. Ecol. Lett. 24, 1193–1204.

De Wit, H.A., et al., 2014. Climate warming feedback from mountain birch forest expansion: reduced albedo dominates carbon uptake. Glob. Change Biol. 20, 2344–2355.

De Wit, H.A., Austnes, K., Hylen, G., Dalsgaard, L., 2015. A carbon balance of Norway: terrestrial and aquatic carbon fluxes. Biogeochemistry 123, 147–173.

Dengler, J., Janišová, M., Török, P., Wellstein, C., 2014. Biodiversity of Palaearctic grasslands: a synthesis. Agric Ecosyst. Environ. 182, 1–14.

Doelman, J.C., et al., 2019. Afforestation for climate change mitigation: potentials, risks and trade-offs. Glob. Change Biol. 26, 1576–1591. https://doi.org/10.1111/gcb.14887.

Ekroos, J., Rundlöf, M., Smith, H., 2013. Trait-dependent responses of flower-visiting insects to distance to semi-natural grasslands and landscape heterogeneity. Landsc. Ecol. 28, 1283–1292.

Ellenberg, H., Weber, H.E., Düll, R., Wirth, V., Werner, W., Paulissen, D., 1991. Zeigerwerte von Pflanzen in Mitteleuropa. Scr. Geobot. 18, 1–248.

Ellis, E.C., Goldewijk, K.K., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. Glob. Ecol. Biogeogr. 19, 589–606.

Emanuelsson, U., Arding, M., Petersson, M., 2009. The Rural Landscapes of Europe: How Man has Shaped European Nature. Formas, Stockholm.

Emanuelsson, U., Norderhaug, A., Thorhallsdottir, A.G., 2024. Biologisk mangfold i naturbeitemark med forskjellig beitetrykk. (Biodiversity in semi-natural pastures under different grazing pressures). Blyttia 82, 117–124.

European Commission 2019. *Climate Action and the Green Deal.* ⟨https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/climate-action-and-green-deal_en⟩.

Finland's Environmental Administration. 2019. Suomen lajien uhanalaisuus (Finlands rödlista 2019) – Punainen kirja 2019. ⟨https://www.ymparisto.fi/en-US/Nature/Species/Threatened_species/The_2019_Red_List_of_Finnish_species⟩.

Griscom, B.W., et al., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. USA 114, 11645–11650.

Hasler, N., Williams, C.A., Denney, V.C., et al., 2024. Accounting for albedo change to identify climate-positive tree cover restoration. Nat. Commun. 15, 2275. https://doi.org/10.1038/s41467-024-46577-1.

Helfenstein, J., Hepner, S., Kreuzer, A., Achermann, G., Williams, T., Bürgi, M., Debonne, N., Dimopoulos, T., Diogo, V., Fjellstad, W., Garcia-Martin, M., Hernik, J., Kizos, T., Lausch, A., Levers, C., Liira, J., Mohr, F., Moreno, G., Pazur, R., Salata, T., Schüpbach, B., Swart, R., Verburg, P.H., Zarina, A., Herzog, F., 2024. Divergent agricultural development pathways across farm and landscape scales in Europe: Implications for sustainability and farmer satisfaction. Glob. Environ. Change 86, 102855. https://doi.org/10.1016/j.gloenvcha.2024.102855.

Hickel, J., 2018. The divide: global inequality from conquest to free markets. W.W. Norton & Company, Inc, New York, NY.

Hillestad, M.E., 2018. *Klimasmart landbruk – lagring av karbon i jord.* Rapport. AgriAnalyse, Oslo, Norway.

Holtsmark, B., 2012. Harvesting in boreal forests and the biofuel carbon debt. Clim. Change 112, 415–428.

Ihse, M. (ed.) 2017. *Utan pengar – inga hagar och ängar.* Kungliga skogs- och lantbruksakademiens tidskrift, 156/5. Kungliga skogs- och lantbruksakademien (KSLA), Stockholm, Sweden.
IPBES. 2022. Summary for Policymakers of the Methodological Assessment Report on the Diverse Values and Valuation of Nature of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). U. Pascual, P. Balvanera, M. Christie et al. (eds.) Bonn, Germany, IPBES secretariat.
Iversen, E.K., Grimsrud, K., Lindhjem, H., 2021. Moving (back) to greener pastures? Social benefits and costs of climate forest planting in Norway. Land Use Policy 107, 104390.
James, J., Harrison, R., 2016. The Effect of Harvest on Forest Soil Carbon: A Meta-Analysis. Forests 7, 308. https://doi.org/10.3390/f7120308.
Jobbagy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423–436.
Kahan, D., 2010. Fixing the communications failure. Nature 463, 296–297.
Kauppi, P.E., Stål, G., Arnesson-Ceder, L., Hallberg Sramek, I., Hoen, H.F., Svensson, A., Wernick, I.K., Högberg, P., Lundmark, T., Nordin, A., 2022. Managing existing forests can mitigate climate change. For. Ecol. Manag. 513, 120186. https://doi.org/10.1016/j.foreco.2022.120186.
Keller, N., Stefani, M., Einarsdóttir, S.R., Helgadóttir, Á.K., Guðmundsson, J., Snorrason, A. et al. (2019) National Inventory Report 2019: emissions of greenhouse gases in Iceland from 1990 to 2017. Submitted under the United Nations framework convention on climate change and the Kyoto protocol. Reykjavik: Environment Agency of Iceland.
Kjønaas, O.J., Bárcena, T.G., Hylen, G., Nordbakken, J.-F., og Økland, T., 2021. Boreal tree species change as a climate mitigation strategy: impact on ecosystem C and N stocks and soil nutrient levels. Ecosphere 12 (11), e03826.
Kolinjivadi, V., Van Hecken, G., Almeida, D.V., Dupras, J., Kosoy, N., 2019. Neoliberal performatives and the 'making' of Payments for Ecosystem Services (PES). Prog. Hum. Geogr. 43, 3–25.
Kumm, K.-I., Hessle, A., 2020. Economic comparison between pasture-based beef production and afforestation of abandoned land in Swedish forest districts. Land 9, 42. https://doi.org/10.3390/land9020042.
Kumm, K.-I., Hessle, A., 2023. The Decline and Possible Return of Silvipastoral Agroforestry in Sweden. Land 12, 940. https://doi.org/10.3390/land12050940.
Lai, L., Kumar, S., 2020. A global meta-analysis of livestock grazing impacts on soil properties. PloS ONE 15, e0236638. ⟨https://doi.org/10.1371/journal.pone.0236638⟩.
Lawrence, D., Coe, M., Walker, W., Verchot, L., Vandecar, K., 2022. The unseen effects of deforestation: biophysical effects on climate. Front. Glob. Change 5, 756115.
Legagneux, P., et al., 2018. Our House Is Burning: Discrepancy in Climate Change vs. Biodiversity Coverage in the Media as Compared to Scientific Literature. Front Ecol. Evol. 5, 175. ⟨https://doi.org/10.3389/fevo.2017.00175/full⟩.
Lennartsson, T. 2016. *Växter och vegetation som biologiskt kulturarv.* Riksantikvarieämbetet, Stockholm, Sweden. ⟨https://www.diva-portal.org/smash/get/diva2:1234857/FULLTEXT01.pdf⟩.
Lindborg, R., Bengtsson, J., Berg, Å., Cousins, S.A.O., Eriksson, O., Gustafsson, T., et al., 2008. A landscape perspective on conservation of semi-natural grasslands. Agric., Ecosyst. Environ. 125, 213–222. https://doi.org/10.1016/j.agee.2008.01.006.
Lindborg, R., Hartel, T., Helm, A., Prangel, E., Reitalu, T., Ripoll-Bosch, R., 2023. Ecosystem services provided by semi-natural and intensified grasslands: synergies, trade-offs and linkages to plant traits and functional richness. Appl. Veg. Sci. 26, e12729. https://doi.org/10.1111/avsc.12729.
Lundgren, E.J., Ramp, D., Rowan, J., Middleton, O., Schowanek, S.D., Sanisidro, O., Carroll, S.P., Davis, M., Sandom, C.J., Svenning, J.-C., Wallach, A.D., 2020. Introduced herbivores restore Late Pleistocene ecological functions. Proc. Natl. Acad. Sci. 117, 7871–7878.
Luyssaert, S., et al., 2018. Trade-offs in using European forests to meet climate objectives, 10 Oct. Nature 562 (7726), 259–262. https://doi.org/10.1038/s41586-018-0577-1.
Määttänen, A.M., Virkkala, R., Leikola, N., Heikkinen, R.K., 2022. Increasing loss of mature boreal forests around protected areas with red-listed forest species. Ecol. Process 11, 17. https://doi.org/10.1186/s13717-022-00361-5.
Martinsen, V., 2011. Sheep grazing effects on soil carbon and nitrogen and implications for runoff water quality at a low alpine site in southern Norway. Effekter av sauebeiting i høyfjellet på karbon og nitrogen i jord og implikasjoner for kvalitet av avrenningsvann. PhD thesis. Norwegian University of Life Sciences, Ås.
Martinsen, V., Mulder, J., Austrheim, G., Mysterud, A., 2011. Carbon storage in low-alpine grassland soils: effects of different grazing intensities of sheep. Eur. J. Soil Sci. 62, 822–833. https://doi.org/10.1111/j.1365-2389.2011.01393.x.
Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.-P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Tamm review: influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. For. Ecol. Manag. 466, 118127. https://doi.org/10.1016/j.foreco.2020.118127.
Mooney, P.A., Lee, H., Sobolowski, S., 2020. Impact of quasi-idealized future land cover scenarios at high latitudes in complex terrain. Earth'S. Future 8, e2020EF001838. https://doi.org/10.1029/2020EF001838.
Norderhaug, A., Austad, I., Hauge, I., Kvamme, M. (red). 1999. Skjøtselsboka for kulturlandskap og gamle norske kulturmarker. Landbruksforlaget. ⟨https://www.miljodirektoratet.no/globalassets/publikasjoner/dirnat2/attachment/636/1.pdf⟩.
Norderhaug, A., Clemmensen, K., Kardol, P., Thorhallsdottir, A.G., Aslaksen, I., 2023. The importance of grasslands in carbon sequestration and climate change mitigation. Clim. Change 176, 55. https://doi.org/10.1007/s10584-023-03537-w.
Nordic Council of Ministers. 2017. *Future Nordic Diets.* ⟨https://norden.diva-portal.org/smash/get/diva2:1163192/FULLTEXT01.pdf⟩.
Norwegian Biodiversity Information Centre. 2021. Hvor finnes de truede artene? Norsk rødliste for arter 2021. Artsdatabanken, Norway. ⟨https://artsdatabanken.no/rodlisteforarter2021/Resultater⟩.
Norwegian Environment Agency, et al., 2013. Planting av skog på nye arealer som klimatiltak – Egnede arealer og miljøkriterier. Report M-26. Norwegian Environment Agency.
Norwegian Environment Agency, et al., 2022. Greenhouse Gas Emissions 1990-2020, National Inventory Report. M-2268. Norwegian Environment Agency.
Öckinger, E., Smith, H.G., 2007. Semi-natural grasslands as population sources for pollinating insects in agricultural landscapes. J. Appl. Ecol. 44, 50–59. ⟨http://www.jstor.org/stable/4123824⟩.
Olofsson, J., Post, E., 2018. Effects of large herbivores on tundra vegetation in a changing climate, and implications for rewilding. Philos. Trans. R. Soc. B 373, 20170437. https://doi.org/10.1098/rstb.2017.0437.
Olsson, M., Andersson, P., Lennartsson, T., Lenoir, L., Mattsson, L., Palme, U., 2012. Land management meeting several environmental objectives. Minimizing impacts on greenhouse gas emissions, biodiversity and water. Knowledge compilation and systems perspective. Swedish Environmental Protection Agency. ⟨https://www.diva-portal.org/smash/get/diva2:1612264/FULLTEXT01.pdf⟩. Report 6505.
Parker, T.C., Thurston, A.M., Raundrup, K., Subke, J.-A., Wookey, P.A., Hartley, I.P., 2021. Shrub expansion in the Arctic may induce large-scale carbon losses due to changes in plant-soil interactions. Plant Soil 463, 643–651.
Parr, C.L., te, Beest, M., Stevens, N., 2024. Conflation of reforestation with restoration is widespread. Sci. Policy Forum 383, 6684, 16 February 2024.
Pearce, E.A., et al., 2023. Substantial light woodland and open vegetation characterized the temperate forest biome before *Homo sapiens*. Sci. Adv. 9, eadi9135. ⟨https://doi.org/10.1126/sciadv.adi9135⟩, 10 November.
Peichl, M., Martínez-García, E., Fransson, J.E.S., Wallerman, J., Laudon, H., Lundmark, T., Nilsson, M.B., 2023. On the uncertainty in estimates of the carbon balance recovery time after forest clear-cutting. Glob. Change Biol. 29, e1–e3. https://doi.org/10.1111/gcb.16772.
Peng, L., Searchinger, T.D., Zionts, J., et al., 2023. The carbon costs of global wood harvests. Nature 620, 110–115. https://doi.org/10.1038/s41586-023-06187-1.
Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., van Wesemael, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. Glob. Chang Biol. 17, 2415–2427. https://doi.org/10.1111/j.1365-2486.2011.02408.x.
Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., Haight, R., Kagan, J., Starfield, A., Tobalske, C., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biol. Conserv. 141, 1505–1524.
Pykälä, J., 2005. Plant species responses to cattle grazing in mesic semi-natural grassland. Agric., Ecosyst. Environ. 108, 109–117.
Rasse, D., Økland, I., Bárcena, T.G., Riley, H., Martinsen, V., Sturite, I., Joner, E., O'Toole, E., Øpstad, S., Cottis, T., Budai, A., 2019. Muligheter og utfordringer for økt karbonbinding i jordbruksjord. NIBIO. Research report 5/36/2019.
Read, D.J., Perez-Moreno, J., 2003. Mycorrhizas and nutrient cycling in ecosystems – a journey towards relevance? N. Phytol. 157, 475–492.
Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9, eadh2458.
Roy, S., Bagchi, S., 2022. Large mammalian herbivores and the paradox of soil carbon in grazing ecosystems: role of microbial decomposers and their enzymes. Ecosystems 25, 976–988. https://doi.org/10.1007/s10021-021-00696-8.
Rusch, G.M., Bartlett, J., Kyrkjeeide, M.O., Lein, U., Nordén, J., Sandvik, H., Stokland, H., 2022. A joint climate and nature cure: A transformative change perspective. Ambio 51, 1459–1473.
Scasta, J.D., Duchardt, C., Engle, D.M., Miller, J.R., Debinski, D.M., Harr, R.N., 2016. Constraints to restoring fire and grazing ecological processes to optimize grassland vegetation structural diversity. Ecol. Eng. 95, 865–875. https://doi.org/10.1016/j.ecoleng.2016.06.096.
Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. B 375, 20190120. https://doi.org/10.1098/rstb.2019.0120.
Sickel, H., Bilger, W., Ohlson, M., 2012. High levels of α-tocopherol in Norwegian alpine grazing plants. J. Agric. Food Chem. 60, 7573–7580. https://doi.org/10.1021/jf301756j.
Sjögersten, S., Alewell, C., Cécillon, L., Hagedorn, F., Jandl, R., Leifeld, J., Martinsen, V., Schindlbacher, A., Sebastià, M.T., Van Miegroet, H., 2011. Mountain soils in a changing climate – vulnerability of carbon stocks and ecosystem feedbacks. Soil Carbon Sensitive Eur. Ecosyst. ⟨https://doi.org/10.1002/9781119970255.ch6⟩ Chapter 6 in Soil Carbon in Sensitive European Ecosystems: From Science to Land Management.
Skarpaas, O. og Halvorsen, R. (eds.). 2022. Skogens dynamikk, struktur og artsmangfold - bakgrunnskunnskap for en ny beskrivelse av skogbestandsdynamikk i NiN. NHM Rapport 111, 1–148. ⟨https://www.nhm.uio.no/forskning/ressurser/publikasjoner/nhm-rapporter/nhm-rapport-111-2022.pdf⟩.
SLU Swedish Species Information Centre. 2020. SLU Artdatabanken. Rödlistade arter i Sverige 2020. SLU, Uppsala. ⟨https://www.artdatabanken.se/publikationer/bestall-publikationer/bestall-rodlista-2020/⟩.

Smith, S.E., Read, D., 2008. Mycorrhizal Symbiosis. Academic Press. https://doi.org/10.1016/B978-0-12-370526-6.X5001-6.

Søgaard, G., Bright, R., Clarke, N., Fløistad, I.S., Granhus, A., Hagenbo, A., Hanssen, K.H., Hietala, A., Kjønaas, O.J., Kühne, C., Rolstad, J., Solberg, S., Steffenrem, A., Stokland, J., Storaunet, K.O., 2023. Oppdatering av kunnskapsgrunnlag for klimatiltak i skog: Gjennomgang av 11 utvalgte tiltak i bestandsskogbruket. NIBIO Rapport 9:22. Norwegian Institute of Bioeconomy Research (NIBIO), Norway.

Sørensen, M.V., Strimbeck, R., Nystuen, K.O., Kapas, R.E., Enquist, B.J., Graae, B.J., 2018. Draining the pool? Carbon storage and fluxes in three Alpine plant Communities. Ecosystems 21, 1–15. https://doi.org/10.1007/s10021-017-0158-4.

Sosa-Hernández, M.A., Leifheit, E.F., Ingraffia, R., Rillig, M.C., 2019. Subsoil arbuscular mycorrhizal fungi for sustainability and climate-smart agriculture: a solution right under our feet? Front. Microbiol. 10, 744.

Speed, J.D.M., Martinsen, V., Mysterud, A., Mulder, J., Holand, O., Austrheim, G., 2014. Long-Term increase in aboveground carbon stocks following exclusion of grazers and forest establishment in an alpine ecosystem. Ecosystems 17, 1138–1150.

Stanley, T., 2024. Carbon 'known not grown': Reforesting Scotland, advanced measurement technologies, and a new frontier of mitigation deterrence. Environ. Sci. Policy 151, 103636.

Steidinger, B.S., Crowther, T.W., Liang, J., Van Nuland, M.E., Werner, G.D.A., Reich, P. B., Nabuurs, G.J., de-Miguel, S., Zhou, M., Picard, N., et al., 2019. Climatic controls of decomposition drive the global biogeography of forest-tree symbioses. Nature 569, 404–408.

Stokland, J.N., 2021. Volume increment and carbon dynamics in boreal forest when extending the rotation length towards biologically old stands. For. Ecol. Manag. 488, 119017. https://doi.org/10.1016/j.foreco.2021.119017.

Strand, L.T., Callesen, I., Dalsgaard, L., de Wit, H.A., 2016. Carbon and nitrogen stocks in Norwegian forest soils - the importance of soil formation, climate, and vegetation type for organic matter accumulation. Can. J. For. Res. 46, 1459–1473.

Strand, L.T., Fjellstad, W., Jackson-Blake, L., De Wit, H.A., 2021. Afforestation of a pasture in Norway did not result in higher soil carbon, 50 years after planting. Landsc. Urban Plan. 207, 104007. https://doi.org/10.1016/j.landurbplan.2020.104007.

Thorhallsdottir, A.G., Gudmundsson, J., 2023. Carbon dioxide fluxes and soil carbon storage in relation to long-term grazing and no grazing in Icelandic semi-natural grasslands. Appl. Veg. Sci. 26, e12757. https://doi.org/10.1111/avsc.12757.

Tonjer, L.-R., Thoen, E., Morgado, L., Botnen, S., Mundra, S., Nybakken, L., Bryn, A., Kauserud, H., 2021. Fungal community dynamics across a forest–alpine ecotone. Mol. Ecol. 30, 4926–4938. https://doi.org/10.1111/mec.16095.

UNFCCC, 2015. The Paris agreement. United Nations Framework Convention on Climate Change. The Paris Agreement | UNFCCC.

United Nations, 2021. SEEA Ecosystem Accounting. United Nations, New York. 〈https://seea.un.org/ecosystem-accounting〉.

Veldman, J.W., et al., 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. BioScience 65, 1011–1018. https://doi.org/10.1093/biosci/biv118.

Veldman, J.W., et al., 2019. Comment on "The global tree restoration potential, 8 Oct 2019 Science 366 (6463). https://doi.org/10.1126/science.aay7976.

Ward, A., Dargusch, P., Thomas, S., Liu, Y., Fulton, E.A., 2014. A global estimate of carbon stored in the world's mountain grasslands and shrublands, and the implications for climate policy. Glob. Environ. Change 28, 14–24.

Wieczorkowski, J.D., Lehmann, C.E.R., 2022. Encroachment diminishes herbaceous plant diversity in grassy ecosystems worldwide. Glob. Change Biol. 28, 5532–5546. https://doi.org/10.1111/gcb.16300.

Wilson, J.B., Peet, R.K., Dengler, J., Pärtel, M., 2012. Plant species richness: the world records. J. Veg. Sci. 23, 796–802.