# Combatting global grassland degradation

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## Abstract

The World's grasslands are under severe threat from on-going degradation, yet they are largely ignored in sustainable development agendas. This degradation is undermining the capacity of grasslands to support biodiversity, ecosystem services, and human wellbeing. In this Perspective, we examine the current state of grasslands worldwide and explore the extent and dominant drivers of global grassland degradation. We identify actions that are critical to the development of socio-ecological solutions to combat degradation and promote restoration of global grasslands. Specifically, we argue that progress can be made by: increasing recognition of grasslands in global policy, developing standardised indicators of grassland degradation, using scientific innovation for effective restoration at regional and landscape scales, and enhancing knowledge transfer and data sharing on restoration experiences. The integration of these strategies into sustainability policy should help to halt grassland

degradation and enhance restoration success, and protect the socio-economic, cultural and ecological benefits that grasslands provide.

Grasslands, comprising open grassland, grassy shrublands and savannah, cover about 40% of the Earth's surface and some 69% of the world's agricultural land area[1-3]. Not only do they serve as an important global reservoir of biodiversity, including many iconic and endemic species, but also, they provide a wide range of material and non-material benefits to humans and our quality of life. These benefits include a wide range of ecosystem services, such as food production, water supply and regulation, carbon storage and climate mitigation, pollination, and a host of cultural services[1-3]. Despite its importance, grassland degradation is widespread and accelerating in many parts of the world[4-6] with as much as 49% of grassland area worldwide having been degraded to some extent[5,7,8].

Grassland degradation poses an enormous threat to the hundreds of millions of people who rely on grasslands worldwide for food, fuel, fibre and medicinal products, as well as their multiple cultural values[9,10]. In terms of livestock production, the global cost of grassland degradation has been estimated at $6.8 billion[11], with the impact on human welfare being particularly severe in regions where most the population is below the poverty line Grassland degradation also creates major environmental problems, given that grasslands play a critical role in biodiversity conservation, climate and water regulation, and global biogeochemical cycles[2,4]. For example, the conversion of tropical grassy biomes to arable cropland poses a significant threat to biodiversity given that they have a vertebrate species richness comparable to forests[12], while the recent expansion of croplands in United States has caused widespread conversion of prairie grasslands, with considerable cost to wildlife[6]. Moreover, the conversion of grasslands to arable cropland and disturbance through overgrazing, fire and invasive species can lead to significant soil carbon loss[13]. Because of these problems, grassland degradation represents a major global challenge that must be addressed if we are to achieve key targets of biodiversity agendas, such as the Aichi Biodiversity Targets[14] of the Convention on Biological Diversity (CBD) and the United Nations Sustainable Development Goals (SDGs), including restoration and sustainable use of terrestrial ecosystems, hunger and poverty alleviation, and climate change mitigation. Combating degradation is also central to the UN Decade on Ecosystem Restoration (2021-2030), which puts a firm focus on the urgent need for strategies for the restoration of degraded ecosystems, including grasslands.

There are multiple, co-occurring drivers of grassland degradation, including over-grazing, eutrophication, land conversion to forestry and crops, land abandonment, invasive species, climate extremes and altered fire regimes (Figure 1). These drivers are also often closely allied to socio-economic drivers, such as spatial expansion of humans, the economics of land use, changes in affluence and dietary preferences, and in land tenure and a lack of enforcement of land use rights. Climate change is also exacerbating grassland degradation, especially due to fires and droughts, which are becoming more common and severe[15]. Despite the importance of grasslands, there has been little progress in finding solutions to halting and reversing global grassland degradation, which is compromising sustainable development and the ecosystem services grasslands provide.

In this Perspective, we consider the current state of grasslands worldwide (comprising open grassland, grassy shrublands, and savannah) and the ecosystem services they provide, and explore what is known about the extent and dominant causes of grassland degradation. We then consider the challenges that grassland restoration efforts face, from societal attitudes to practical efforts, and identify actions that are critical to the development of socio-ecological solutions to combat degradation and promote restoration of global grasslands. We argue that progress can only be made through increasing recognition of grasslands in regional and global policy, developing standardised indicators of degradation and restoration, introducing ecological innovation into restoration, and enhancing knowledge transfer and data sharing regarding restoration experiences. If adopted, these measures should benefit global policy initiatives to tackle ecosystem degradation and restoration, and protect the many socio-economic, cultural and ecological benefits that grasslands provide.

## Defining grasslands

A key issue in the poor recognition of grasslands in policy is a lack of clarity in defining the grassland biome. Grasslands can be defined in terms of both what they are, for example dominated by grasses and graminoids, and what they are not, for example lacking extensive trees or scrub. Broadly defined, grasslands include, amongst others, European meadows and pastures, North American prairies, South American cerrados and pampas, African savannahs, Australian rangelands, and Asian steppes. In many parts of the world and for many ecologists and conservationists, ‘natural grasslands’ are the most important biome, and these are found in both the tropical and temperate zones. Natural grasslands are generally found where the climate and/or soils cannot support woody plant growth, such as above the tree-line or in the dry-lands of the world. Often such factors interact with natural disturbance such as by fire or wild grazers, which constrain growth of woody plants and maintain the grasses and associated low-growing plants[16]. Indeed, changes in the balance of these interacting factors can trigger radical change. For example, many parts of Africa (and elsewhere) are seeing ‘woody plant encroachment’ linked to a decline in burned area along with warmer and wetter climates[17], while the Holocene transition from extensive grasslands into the Sahara Desert was likely due to the onset of drier conditions at the end of the African Humic Period[18].

So-called ‘semi-natural grasslands’ are also important ecologically, and receive special attention in Europe[19], where they are important reservoirs for biodiversity[20]. Such grasslands have been produced by centuries of human activity, generally by traditional, low-intensity agriculture involving livestock grazing, hay-cutting, and sometimes management with fire. Semi-natural grasslands have been created by clearing natural vegetation such as forest, but also by modifying natural grasslands. As agriculture has become increasingly intensive over the last century, ‘improved’ grasslands of low plant species diversity have come to dominate in many parts of the world, characterised by the use of inorganic fertilisers, high stocking densities of productive livestock breeds, and often frequent re-sowing with high-yielding plant varieties. In this Perspective, we focus on natural and semi-natural grasslands, with improved grasslands generally considered a form of grassland degradation in terms of loss of biodiversity and many ecosystem services[19].

The vegetation of natural and semi-natural grasslands, while typically dominated by grasses and graminoids, often has a large forb component and even scattered trees or scrub. Indeed, in terms of species richness, forbs dominate grasslands worldwide, and are often the most species-rich functional group, for example in North American prairie, African savannah, Mongolian steppes, and South American pampas, campos and cerrados[21]. According to some definitions, grasslands can also have a relatively high tree cover before they become classed as forest[22]. Natural grasslands are often grazed by wild herbivores, including many large mammals, but large areas are also used for domestic livestock. As such, meat, dairy and other livestock products such as wool comprise the most prominent ecosystem services provided by both natural and semi-natural grasslands. The livelihoods and cultures of some traditional communities revolve almost entirely around their livestock systems[20,23], which in turn maintains the diversity of livestock breeds[24].

Grasslands support a huge amount of biodiversity, hosting numerous species not found in forests[12,25] and distinct assemblages of native large herbivores and their predators, many of which are threatened by extinction due to the combined impacts of hunting, encroachment by humans and their livestock, and habitat loss[26]. Many of these species are highly charismatic and globally renowned, such as bison, wolves, rhinos and lions, and hence provide cultural services, such as ecotourism, and related benefits[27]. It is perhaps less acknowledged, however, that grasslands provide many other ecosystem services, including holding flood waters, providing clean water, regulating soil erosion, and providing wild food and medicines[10]. These services and their importance vary geographically in relation to local environments and the demands from people[10]. Cultural services include aesthetic value, hunting, heritage values and resources for tourism and recreation, especially where grasslands define the ecology and culture of an area[28].

The role of grasslands in carbon storage is often overlooked, although estimates suggest that they contain 30% of the world's soil carbon stock[29] and that natural and sparsely grazed grasslands act as a significant global carbon sink and provide an important climate cooling service[30]. However, there is a global trend of grasslands transitioning towards a net warming effect on climate due to increased greenhouse gas emission associated with higher livestock numbers and management intensification[30]. Furthermore, natural and sparsely grazed grasslands contain "irrecoverable carbon" that is vulnerable to land use conversion; once lost, this carbon is not recoverable over timescales relevant to climate mitigation[31]. Nevertheless, there is high potential for increasing soil carbon sequestration in grasslands via improved grazing and by arresting grassland conversion and degradation[32].

## Extent and drivers of degradation

Globally, estimates suggest that as much as 49% of grassland area has been degraded to some extent[5,7,8], although there is much uncertainty given that definitions of both grassland and degradation vary. For example, improved grasslands can be conflated with the natural and semi-natural grasslands considered here. The IPBES Assessment Report on Land Degradation and Restoration[33] suggests that about half of the global natural grassland area is degraded to some extent. More specific estimates include: about 90% of the UK's semi-natural grasslands lost since the 1940s[19], up to 90% of the vast grasslands of the Qinghai-Tibetan Plateau degraded[34], and over 60% of the former grassland area of southern Brazil lost[35]. As illustrated by this geographic range, threats to natural and semi-natural grasslands are present across most of the globe. However, current threat levels seem particularly high in the tropics[16], while loss of the small remaining areas of western European grassland has largely slowed[36]. It is likely, however, that ongoing environmental change will pose further threats to all grasslands. Climate change has been shown in the past to cause grassland loss and degradation, and projected future climate change will likely combine with human activities to cause increased woody plant encroachment in some areas and desertification in others[37,38]. An increasing and immediate concern is the planned planting of trees on important grasslands across the globe, ostensibly to meet afforestation targets for climate change mitigaton[39].

There are many drivers of grassland degradation, which we classify for heuristic purposes into three broad types: disturbances, anthropogenic inputs, and land use change. The degree of disturbance is important; too little can drive a transition into more woody vegetation, while too much can lead to soil erosion and desertification. In Europe, many semi-natural grasslands were abandoned and lost to scrub in the 20th century as these low intensity grazing systems became uneconomic[40]. Over-grazing or a heightened fire frequency can disrupt vegetation cover, cause soil erosion, and lead to desertification[41]. Considering the intensity of anthropogenic inputs, natural and semi-natural grasslands tend to receive low-intensity management, contrasting with the fertiliser inputs and re-sowing with productive cultivars to support heavy grazing in improved grasslands. More general human inputs, such as through atmospheric nitrogen deposition, can have similar effects to agricultural intensification[42]. The third type comprises humans actively converting grasslands to other land uses, for instance to arable farming, built infrastructure, and to forestry[35,43]. A related problem is invasion by introduced woody plants, such as *Prosopis juliflora,* which change the land cover[44].

These three drivers of grassland degradation interact and are also exacerbated by climate change. For example, natural grasslands in the Americas, Australia and Africa are being degraded due to woody plant encroachment, with the major causes thought to be a combination of higher atmospheric $CO_2$ concentrations, reductions in fire or grazing pressures, and warmer and wetter conditions[45]. Conversely, in many parts of the world, such as Central Asia and Africa, over-grazing combined with more intense and frequent droughts is exacerbating grassland desertification and degradation[46].

## Halting degradation and promoting restoration

Here, we propose five actions that should be deployed to develop effective socio-ecological solutions to the degradation and restoration of global grasslands.

***Policy recognition of grasslands.*** A key factor contributing to the degradation of grasslands is the lack of representation of grassland in national and international policy. In fact, grasslands are in many ways the 'Cinderella' of the world's biomes, with the scientific and political focus of global sustainability policy being on ecosystems such as oceans, freshwaters, forests and croplands. Indeed, despite suffering some of the highest rates of degradation of any biome, Dudley et al[47] reported that only 8% of grassland and savannah biomes protected. As such, there is a pressing need for national and global policy to recognize the role of grasslands in addressing climate mitigation, food security, biodiversity conservation and poverty alleviation.

Numerous examples exist of national and international policies on environment and sustainability that have ignored grasslands. For example, halting and reversing ecosystem degradation is a central goal of the SDGs (Goal 15), the UN Framework Convention on Climate Change (UNFCCC), and the Convention on Biological Diversity (CBD), but there is no explicit mention of grasslands in any of them. The SDG targets also fail to mention grasslands, whereas forests, oceans and coastal ecosystems are repeatedly referenced in targets and indicators. Further, while grassland regions contain around half the world's 234 Centres of Plant Diversity - sites of global botanical importance based on endemism and species richness - they were not mentioned in the Aichi Biodiversity Targets of the CBD[14]. The European Biodiversity Strategy to 2020[48] also makes little mention of grasslands, whereas forests feature heavily.

Pressures on grasslands have also been accentuated through the unforeseen consequences of global and national environmental and socio-economic policies. In particular, grasslands are increasingly targeted in carbon sequestration programs that emphasize tree planting, such as REDD+ and China's Grain-to-Green Project, which often leads to their degradation. The Chinese government, for example, has invested heavily in tree planting, with tree coverage of previously non-forested areas increasing at an average rate of 0.15 million hectares per year over the last 25 years. However, there is major concern that tree planting in arid and semi-arid grasslands with water-demanding trees is exacerbating grassland degradation, reducing plant diversity, damaging soils, and increasing water shortages[50-52]. Also, large tracts of grassland in Brazil have been identified as targets for tree planting, posing a major threat to these ancient and highly diverse ecosystems[25]. An estimated 7.41 million ha of eucalypt and 2.07 million ha of pine plantation already occupy mostly former savannahs and grassland, at an astonishing rate of 0.4 million ha per year from 2013-2017[53]. Indeed, it has been calculated that meeting land restoration and protection targets would increase global tree cover by 4M $km^2$, often at the expense of grasslands[54]. Furthermore, models of global forest restoration potential have identified natural grasslands as sites for restoration using tree planting, with potential to contribute to carbon sequestration and climate mitigation[55]. The logic of such proposals for climate mitigation, however, is increasingly been challenged on the basis of their damaging impact on natural grasslands and because their carbon sequestration potential is considered inflated[39,56.]

Grasslands can be more resilient carbon sinks than forests[57], and afforestation can cause soil carbon loss[58,59], soil acidification and nutrient-depletion[60], especially when trees are planted in natural grasslands[59], making them prone to carbon loss from fires[56.] Large-scale afforestation also leads to changes in surface albedo, given that forests absorb more short-wave radiation than grasslands, thereby creating a warming effect[60.61]. As such, changes in albedo resulting from afforestation can reduce or even negate benefits of increased carbon capture, potentially leading to a net warming effect of tree planting[60,61]. Another issue is that policies such as REDD+ focus primarily on carbon sequestration in aboveground tree biomass, while healthy and restored grasslands can store comparable amounts of organic carbon as forests, but mainly belowground[57,63.] Grasslands have also been shown to be more effective than forests in providing soil erosion control and water protection in semi-arid ecosystems[64], and the conversion of grassland to forest, either through natural regeneration or afforestation, can be highly detrimental to people who depend on grasslands for forage, game habitat, water reserves, and cultural services[56,65,66.]

The lack of emphasis on grasslands in international and national policies has a long history. The 1954 Constitution of the People's Republic of China, for example, recognised forests, mines, rivers, wastelands (which probably included grasslands) and other resources, while grassland law, aimed at protecting, developing and making rational use of grasslands, did not appear in the constitution until 1985. Grasslands in India have also been historically undervalued in national policies, and even today they are widely considered to be unproductive wastelands of limited value, leaving them vulnerable to land conversion[67,68]. In Brazil, while major progress has been made in the conservation of forest ecosystems, non-forest biomes, including the Cerrado and Pampas grasslands, have been largely neglected, despite being among the most species rich grasslands in the world[69]. Similarly, and despite their ancient origin, Asian savannahs have been considered to be degraded forest since colonial times, which has led to inappropriate management and policies that promote their degradation and loss[70].

If grasslands are to be valued and managed sustainably, then both global and regional policy must change to recognize the value of grasslands as providers of multiple ecosystem services and hotspots for biodiversity, and to establish targets for their protection and sustainable management. Approaches could comprise specific inclusion of grasslands in conservation laws and policies and ensuring conservation policies do not have perverse consequences for grasslands, such as promoting fire suppression or afforestation. New policies to promote and fund appropriate management and restoration of grasslands are also needed, including penalties for degrading activities such as overgrazing. As an example, China's grassland law includes a range of policies that have been implemented to protect healthy and restore degraded grasslands[71].

***Standardised assessment.*** The coherent evaluation of grassland condition across the World requires standardised approaches. These should assess the severity of grassland degradation and its consequences for biodiversity and ecosystem services and evaluate the success of restoration schemes. Currently, restoration efforts are disjointed across regions and carried out by a wide range of organisations, which often leads to incompatible and inaccessible datasets, and a lack of communication about successful methods[72,73]. The diversity of grasslands across and within regions, and the many drivers of degradation, mean a fully uniform set of guidelines is impractical. Yet, we suggest that standardised approaches are needed to underpin effective decision-making.

Progress can be made by defining grassland degradation from a socio-ecological perspective, where grassland is considered degraded if the supply of multiple ecosystem services falls short of that demanded by stakeholders[74]. Different stakeholder groups prioritise different combinations of ecosystem services[75,76]; as such, the definition of degradation depends upon the stakeholder, and needs to be tailored accordingly (Figures 2-4). In some cases, grassland degradation is apparent to all stakeholders, for instance when overgrazing leads to loss of vegetation, reductions in soil organic matter and consequent soil erosion[77]. However, in other cases, perceptions of degradation and restoration success may differ: the increase in plant production but accompanying loss of plant species diversity resulting from fertilizer use might be considered an improvement by pastoralists, due to increased forage production, but as degradation by conservationists concerned with biodiversity protection[78].

The severity of degradation and the relative benefits of different grassland restoration practices can be assessed by combining measures of ecosystem service supply and stakeholder priorities and demands. Such measures can show how alternative restoration options differ in their impacts on ecosystem service supply and in their resulting benefits for different stakeholder groups. We recommend that this is achieved via a general five-step approach for standardising the assessment of grassland degradation and restoration (Figure 2). The results of this approach can also be used to support negotiation over restoration management.

The first step is to assess the demand for, and relative priority of, different ecosystem services by multiple stakeholder groups, for instance via social surveys of many stakeholders, or representative community leaders[75,39] (Figure 2). It is vital that all major stakeholder groups are represented and the full range of relevant ecosystem services, including non-material (cultural) benefits considered, otherwise bad management decisions may result and potential conflict[80]. Once ecosystem service demand is determined, indicators need to be identified and measured for each of the services. We propose that these should fall into two classes: general indicators, which measure ecosystem services for all stakeholder groups; and specific indicators for services used by a subset of the stakeholder community. In step 2, general indicators should be inexpensive and easy to measure over large scales and relate to key regulating functions that underpin all other ecosystem services. Such properties could include the cover and type of vegetation present, aboveground biomass, and soil properties such as organic matter, nutrient content, and pH. A presentation of possible measures and the ecosystem services they represent is in Table 1.

The next step is to find tailored indicators for the specific ecosystem services used by different stakeholder groups. While the general indicators proposed above provide broadly comparable information on grassland condition, perceptions of grassland degradation differ between stakeholder groups[81]. Therefore, in addition to general indicators, other variables should be identified locally for these context-specific ecosystem services. These services and their indicators should be identified via stakeholder engagement, with indicators being developed according to local conditions. In the French Alps, for example, surveys identified that aesthetic value of mountain grasslands was essential to local farmers and tourists, and related not only to flower diversity, but also to the absence of a build-up of plant litter[82]. As another example, the cover of woody species can be used as an indicator of the vital regulating service of shade provision in East African grasslands[83]. Visually estimable indicators can also be employed in such assessments to ensure both relevance and cost-effectiveness.

In the fourth step, general and specific measures can be combined to calculate an integrated index of grassland condition that can be related to local environmental conditions, management factors, global change drivers and restoration management. The creation of such indices can be achieved by adapting approaches developed for measuring the co-delivery of multiple ecosystem services based on stakeholder preferences[74,84], and other participatory multi-criteria analyses of ecosystem services[85]. Both approaches can also be used to weigh the measures included in the calculation of the index, for example by encouraging representatives of different stakeholder groups to assign scores to the ecosystem services considered[83]. In the final step, we suggest that conclusions from this standardised approach are used to inform management decisions regarding which restoration options should be employed and where. This is best resolved in participatory approaches, so that stakeholders share understanding, and conflict is minimised (Figure 2, and see Shared Understanding section below). The best options for whole communities can be estimated by weighting stakeholder groups equally in a community level metric, or by evaluating which restoration options minimise trade-offs between groups. As a single restoration practice may not benefit all stakeholder groups, the compartmentalisation of the landscape into different restoration options should also be considered (Figure 2).

The approach presented here would not only allow for more detailed examination of grassland condition with regards to local needs, but also a better means of assessing the severity of grassland degradation and restoration success at both local and larger scales. In figures 3 and 4, we demonstrate how this approach can be applied in practice and how different restoration strategies create trade-offs or synergies for stakeholders in two regions: temperate European grasslands and in the arid and semi-arid grasslands of Eastern Africa (Figures 3 and 4). We advise readers to see Supplementary Material for details on the source of these estimates, and Manning et al.[74] for a tutorial and R code for calculating such metrics.

***Shared understanding and trade-offs***. When assessing grassland restoration options that best suit different stakeholder groups, there will likely be differences in preferred options (Figures 3 & 4), which might cause disagreement and conflict. To address this, there is a need for shared understanding, based on best knowledge and practice and operational constraints, of the potential for different grassland restoration options to supply different ecosystem services[86,87], which can be quantified using the same tools as described above for assessing degradation. Such an approach could help identify which restoration option might best deliver the needs of all stakeholder groups, thereby supporting resolution of disagreements and conflict.

To illustrate these trade-offs and how they may be resolved we present two detailed examples in which the standardised approach described above is applied. In both, fundamental trade-offs caused by degradation and restoration options prevent the co-supply of all ecosystem services. The first example is taken from European grasslands (Figure 3), where extensive management promotes functions related to water and soil carbon storage, which support ecosystem services linked to water and climate regulation. In contrast, intensive management with fertiliser use and high grazing pressures leads to faster rates of nutrient cycling and higher plant productivity, thereby promoting provisioning services[78,88]. However, intensive management also reduces plant and soil biodiversity and causes soil compaction, which diminishes the supply of several ecosystem services demanded by stakeholders, leading to reduced overall benefits to stakeholder groups (Figure 3). To reverse these impacts, restoration to high diversity grassland can enhance the supply of multiple ecosystem services, and therefore provides substantial benefits to all stakeholder groups. Despite this, the abandonment of agricultural management altogether, which leads to woody plant encroachment, may be the best option to provide some of the benefits prioritized by national decision makers, namely water quality and climate regulation. Given these various trade-offs, and depending on European or national objectives, and on regional conditions[89], collective choice would likely favour a mosaic of all three grassland types with the restoration of high diversity grassland, accompanied by the segregation of intensive production and climate regulation into specific regions and landscapes[90].

The second example is taken from arid and semi-arid Eastern Africa (Figure 4), where nomadic pastoralists favour provisioning services of forage production and natural products from grasslands, while charcoal producers derive their livelihoods from native woody vegetation and, increasingly, from invasive woody species such as *Prosopis juliflora*. Because the invasion of *P. juliflora* transforms grasslands into scrubland with bare soil[91], the supply of most ecosystem services demanded by stakeholders is greatly reduced, but fuel wood and charcoal production are promoted[83]. The supply of other services, such as soil carbon storage, is context-dependent; soil conditions are improved when *P. juliflora* invades grasslands degraded by overgrazing and other forms of mismanagement. However, if undegraded grassland is invaded, the supply of these services is reduced[92] and all stakeholders, apart from charcoal producers, lose ecosystem service benefits, and so perceive the invasion as degradation. This example also clearly demonstrates that successful restoration depends on stakeholder perspectives as all restoration options benefit the priority services of some groups, while diminishing those of others. These constraints preclude a single win-win-win restoration option. Therefore, regional-scale restoration that establishes a landscape mosaic, including livestock grazing and patches of conserved or abandoned land, is likely to be required for all three stakeholder groups to be satisfied. It should be noted, however, that such a landscape mosaic would require continuous management of *P. juliflora*, otherwise it will re-invade grasslands and conserved land.

Identifying the presence and cause of trade-offs is a first step towards management and policy solutions to grassland degradation. We suggest that the approaches presented here could be combined as a decision support tool in ecosystem management[93]. This can be used as part of a 'landscape approach' to management, which emphasises close collaboration and shared understanding between stakeholder groups to identify and mitigate land management conflicts. Depending on context, this approach could allow for the allocation of different restoration options to different sections of the landscape, as in semi-arid grasslands of Eastern Africa (Figure 4), or the identification of win-win options where a single restoration practice might suit multiple stakeholder groups, such as in European grasslands (Figure 3). These approaches are already considered in existing grassland management approaches, such as the Participatory Rangeland Management (PRM) approach, which has been developed to improve the sustainable management of rangeland resources and their security of access for local rangeland users in arid and semi-arid grasslands[94]. This approach includes a step where stakeholder groups, through extensive meetings, discussions and negotiations, develop a rangeland management agreement that considers the needs of all stakeholder groups involved. This agreement should ultimately become a binding contract document between a representative rangeland management institution and the appropriate government authority. The PRM was initially developed by a consortium including the International Livestock Research Institute in Ethiopia and has recently been applied in Kenya and Tanzania[95]. A similar approach called Participatory Rangeland Management Planning (PRMP) has been adopted by the International Union for Conservation of Nature (IUCN)[96].

We note that complex trade-offs might prevent the formulation of simple solutions, and in such situations multi-criteria decision analysis (MCDA) can be used to support deliberation among groups and help steer them towards a compromise where local communities have a voice and multiple perspectives of grassland degradation are accommodated[97-98]. Advanced MCDA approaches also allow for the incorporation of socio-economic factors, such as access rights and ease, and power relationships between stakeholder groups across scales, which will determine the ultimate benefits of ecosystem services to different groups[99]. However, to ensure better outcomes from decision tools such as MCDA it is also important to consider optimal allocation and prioritisation of limiting resources to actions[100], especially since funds for grassland restoration are often limited.

***Exemplars of grassland restoration.*** Evidence of success or failure of grassland restoration programmes is scant[101,102]. Accordingly, there is a need for standardised and accessible reporting of restoration successes and failures, and ongoing monitoring of grassland restoration programmes and their outcomes in different parts of the world. An important step for achieving this is the sharing of restoration knowledge which requires the formation of networks of scientists and practitioners that exchange knowledge on successful, but also unsuccessful, restoration efforts (Box 1). Such networks could form a platform for case studies illustrating novel ideas and approaches to restoration at local and landscape scales in different parts of the world (Table 2; Figure 1). They could also illustrate the successful translation of research into improved restoration and management, which should include the co-creation and co-implementation of technical solutions to grassland restoration, and the political and socio-economic conditions that made them possible.

Case studies reporting technical solutions to grassland degradation at scales of hundreds to thousands of hectares are particularly scarce, especially for developing countries in semi-arid and arid regions of the world. Studies summarized in Table 2, however, indicate that grassland restoration is feasible, at least starting from low levels of degradation, and that technical and socio-ecological solutions often need to be combined to achieve long-term management goals. For example, grasslands in Inner Mongolia are challenged with a diverse set of stakeholder demands, including the need for environmental services, such as increased soil carbon storage, and the local herders' wish to retain traditional livelihoods while increasing their income, and an increasing demand for red meat by the wider population in China and elsewhere[71]. To address these demands of various stakeholder groups, a grassland management system was developed that built on optimizing income from livestock production per unit area, which was achieved by increasing animal growth rates (and thus reaching marketable size earlier) by decreasing livestock numbers by approximately 50%[71]. Thus, the system created a win-win situation by improving local herders' income and enabling the recovery of grasslands and associated ecosystem services (Table 2).

In northern Ethiopia, several years of excluding livestock from mountain grasslands led to the recovery of plant species richness, forage and wood production, and soil health, and thus helped to improve the supply of services prioritized by local stakeholders[103-105]. However, the uptake of technical solutions for restoring degraded grasslands depends on socio-economic factors, including reconciliation with traditional land-tenure systems, well-established communication pathways, and supporting institutional settings and policies (Table 2). For example, implementation of sustainable grassland management in Inner Mongolia benefits from recent efforts of the Chinese government to emphasize sustainable grassland management in agricultural policies[105], while the success of the grazing exclosure programme in northern Ethiopia will depend on successful communication and negotiations between local stakeholder groups and policy as well as among local stakeholders to ensure land use enforcement and sharing of management responsibilities and harvesting benefits[103-105].

***Research innovation:*** A new generation of environmental research offers the potential to improve the assessment of grassland degradation and provide novel solutions to restoration. At global and regional scales, remote sensing technologies can evaluate both the extent and status of grasslands and inform the spatial targeting of large-scale restoration efforts. For example, maps of general degradation indicators, such as primary productivity, standing biomass, soil moisture, phenology, soil organic carbon[106-108], could be combined with spatial information on climate, edaphic and socio-economic data to identify national and global patterns of grassland degradation and pin-point locations where restoration efforts may have the greatest impact. While current global maps of primary productivity and biomass carbon still need improvement, they offer a means to monitor the dynamics of grassland aboveground biomass and evaluate the degradation of global grasslands[109,110].

In regions where semi-natural grassland remnants are fragmented and persist within a matrix of forested or intensive agriculture land uses, new research could facilitate landscape and regional scale restoration of inter-connected grasslands. There is increasing evidence that grassland dynamics and function are enhanced by connectivity that encourages flows of species and biogeochemical processes[111,112]. In theory, such spatial networks have improved resilience to perturbations, such as climate extremes, and the ability to adapt to a changing environment[113]. Research is needed to apply these emerging concepts to landscape design of restoration that allows ecological flows of species and processes[114,115], although at a practical level, there is already considerable opportunity to trial these approaches in large-scale restoration programmes[116]. Such approaches also require improved understanding of the tele-coupling of different landscape elements, whereby human-induced processes in one area impact on distant areas. For example, pastoralists in arid regions depend on grazing areas along major water bodies, which are also of interest to other stakeholders for crop production or biodiversity conservation[117]. Loss of such grazing areas forces pastoralists to overgraze rain-fed grasslands elsewhere, leading grassland degradation[118].

Another fast-developing area of ecological research that could assist grassland restoration programmes concerns the application of knowledge of aboveground-belowground interactions[119,120]. A wealth of studies show that high grassland plant diversity can enhance multiple ecosystem functions, both above- and belowground, and increase the resistance of plant production to environmental perturbations, such as climate extremes[121-123]; such knowledge could be applied to degraded grassland to restore ecosystem functions and their resilience to environmental change[124,125]. Benefits can also be realised through informed selection of plant species based on functional traits, especially root traits, which has been shown to be an effective way of enhancing grassland multifunctionality[126] and the physical properties of degraded soils[127]. Research points to the potential of soil inoculation and plant translocation from donor sites to enhance the recovery of degraded ecosystems and steer plant community development[128,129]. There is also increasing awareness that biodiversity at multiple trophic levels is critical to developing multifunctional grassland ecosystems[130]. Studies show, for instance, that diversifying livestock promotes plant diversity and grassland multifunctionality[131], especially at moderate levels of grazing[132], and multi-trophic restoration might be implemented via improved understanding of interaction networks and how interventions can facilitate robust networks in restored ecosystems[133].

A potential hurdle to the adoption of new research innovation is that the majority of scientific knowledge underpinning grassland restoration comes from studies done at a local scale and in a handful of regions, especially North America, Australasia and Europe. As such, there is a need for new, long-term research to underpin approaches to large-scale restoration of degraded grasslands, especially in Asia, Africa and South America where grassland degradation is widespread[134]. One solution to these geographic gaps might be the use of meta-level analyses[135-136] and data collected using standardised methodology from globally distributed grassland studies such as the Nutrient Network[137] and HerbDivNet[138]. These can help to identify generalisable impacts of biotic and environmental drivers and disturbances, such as grazing and nutrient enrichment, on grassland diversity and function, that may be transferred to regions where data is lacking. It should be noted, however, that large gaps in environmental and management conditions still need to be filled, and the ecological context will affect the specific applicability of any generalisations[139]. At all scales, new technology and practices need to be embedded within socio-ecological approaches to grassland restoration to ensure empowerment of local people and best outcomes for their quality of life.

## Summary and future perspectives

Despite progress in understanding the causes and consequences of grassland degradation, and in developing restoration techniques, there remain many barriers to halting grassland degradation and effective restoration. Here, we have argued that overcoming these barriers requires an integrated socio-ecological approach to grassland degradation and restoration, that not only demands greater recognition of grasslands in global policy, but also standardised approaches for assessing grassland degradation and restoration success. It also requires the adoption of recent innovations in environmental sciences for both detecting grassland degradation and enhancing restoration success, along with enhanced knowledge transfer and data sharing regarding restoration experiences.

Many examples exist of national and international sustainability policies that have ignored grasslands, including the SDGs and CBD. Giving due attention in sustainability policy to grasslands and the ecosystem services they provide, on a par with other biomes such as forests, is therefore essential for the future protection of healthy grasslands and restoration of those that are degraded. The UN Decade on Ecosystem Restoration (2021-2030) and CBD post-2020 global biodiversity framework provides an opportunity to set future targets for the protection, sustainable management and restoration of grasslands, and prevent damaging practices such as the planting of trees in natural grasslands[140]. Put simply, if grasslands are to be managed sustainably, then both global and regional policy must be revised to recognize the value of grasslands for multiple ecosystem services and establish targets for their protection, restoration and sustainable management. There is hope in some recent initiatives. The Worldwide Fund for Nature has recently launched a 'Global Grassland & Savannah Dialogue Platform', with the aim to "develop consensus around human and biological importance of these ecosystems". The UN Decade on Ecosystem Restoration has recently added 'grasslands, shrubland and savannahs' to their set of focal ecosystems. Furthermore, while the Aichi targets of the CBD largely ignored grasslands, and the draft of its post-2020 framework lacks specificity, the most recent synthesis of the proposals of the parties includes mentions of grasslands (albeit other ecosystems such as forest and wetlands are discussed more frequently).

Whilst we demonstrate how our five-step approach can be applied using specific case studies, future research is needed to test this approach in different contexts and at local and larger scales. Research is also needed to develop and test promising new ways of assessing grassland degradation and restoration, and to harness ecological knowledge for restoration success. This will require ambitious, interdisciplinary national and international research programmes of the kind that could be facilitated by major research and innovation schemes targeted at achieving Sustainable Development Goals. We hope the approach we present provides a basis for such future research aimed at the assessment of grassland degradation and restoration in the context of stakeholder needs.

The actions we raise for developing effective socio-ecological solutions to the degradation and restoration of global grasslands are not exhaustive and many challenges remain. Nevertheless, we hope that they provide a guide to future research and policy needs for halting grassland degradation and achieving restoration success. We also hope that they serve to raise awareness of the plight of global grasslands and the need for urgent action to halt grassland degradation and enhance restoration success, thereby conserving the many socio-economic, cultural and ecological benefits that grasslands provide.

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**Box 1: Platforms for effective grassland restoration**

Examples of platforms that provide information on successes and failures of grassland restoration programmes are beginning to emerge. The Society for Ecological Restoration (SER) recently launched their Restoration Resource Centre, an online, publicly accessible platform for exchanging knowledge and experience through ecological restoration projects, publications, and other resources from around the world. The World Overview of Conservation Approaches and Technologies (WOCAT) database provides a format and a platform for knowledge exchange regarding Sustainable Land Management (SLM) technologies and approaches and is recognized as the primary recommended database by UNCCD. The Global Landscape Forum (GLF), led by the Centre for International Forestry Research (CIFOR) and supported by the UN and World Bank, provides a mobile platform for discussions leading to action on sustainable land use, including land restoration. Grasslands are currently underrepresented within these databases, which are still under development and continually being expanded. Nevertheless, they demonstrate the potential for user-driven platforms to provide valuable insight into effective restoration practices in different parts of the world. To be effective, such platforms should include a wide range of restoration programmes, both local and regional, and small and large scale. They should also include less successful programmes and identify why they have not reached their objectives. By comparing case studies, it is possible to understand how the effectiveness of specific restoration methods differ geographically and depending on the degree of degradation and socio-ecological context, the first step towards finding general rules, both social and ecological, for successful restoration.

## Figure legends

**Figure 1.** The extent of degraded grasslands worldwide with examples of paired non-degraded (left) and degraded (right) grasslands from different locations around the world. Grassland classification follows the UN FAO Land Cover Classification System (LCCS) (data downloaded at https://lcviewer.vito.be/2015[141] with tundra ecosystems excluded. Degradation is measured as greenness changes, as measured by rain use efficiency (RUE) adjusted Sum Normalized Differential Vegetation Index (NDVI) between (1981-2015)[142] with regions showing a reduction in greenness of 0.01 being classed as degraded. Therefore, much degradation involving vegetation change is not shown. Degradation is caused by many factors, including overgrazing, fertilization, tree planting, and invasive species. Image credits: United States (L. Brudvig), United Kingdom (L. Hulmes), Qinghai-Tibet Plateau, China (R. Bardgett), Inner Mongolia (R. Bardgett), Brazil (G. Durigan), Kenya (R. Bardgett), India (M. Sankaran, S.K. Chengappa), and Australia (S. Prober).

**Figure 2.** Standardised assessment of grassland degradation and restoration. This conceptual figure shows the steps required to assess grassland condition and select restoration options. The relationship between this approach and the other strategies described in this article are shown on the side panel. For specific and quantitative examples of these steps, see Figures 3 and 4.

**Figure 3**. Assessing ecosystem service trade-offs in degraded and restored European grasslands. In this system degradation caused by intensive agriculture reduces plant and soil biodiversity and causes soil compaction. This diminishes the supply (SD) of ecosystem services demanded (Di) by stakeholders, resulting in a low multifunctionality (MF) for all stakeholder groups (Di x SD). Restoration to high diversity, perennial grassland (SR1: Perennial grassland) enhances the supply of multiple ecosystem services, though only moderately for fodder production and climate regulation through carbon storage. Thus, among restoration options it provides the greatest multifunctionality to all stakeholder groups. Restored perennial grassland also provides the best option for priority ecosystem services (PF) for conservationists, but also for local farmers given their demand for soil fertility and cultural identity, which compensates for lower fodder production than intensive grassland. However, abandonment of agricultural management may be seen as favourable by some national decision makers due to their prioritization of water quality and climate regulation.

**Figure 4.** Assessing ecosystem service trade-offs in degraded and restored grasslands in arid and semi-arid Eastern Africa. In these regions, invasion of alien woody plants such as *Prosopis*

*juliflora* transforms grasslands into scrubland with bare soil. While the supply (SD) of most ecosystem services demanded (D2) by stakeholders is greatly reduced by this invasion, fuel wood and charcoal production are promoted. The supply of other services, such as soil carbon storage, is context-dependent; if grassland previously degraded by overgrazing and other forms of mismanagement is invaded, then soil conditions are improved. However, if healthy grassland is invaded, the supply of these services is reduced. All stakeholders, apart from charcoal producers, lose ecosystem service benefits (D2 x SD) if undegraded grasslands are invaded by *P. juliflora*, and so perceive it as degradation. Restoration options have differing impacts on stakeholder groups. Sustainable livestock grazing (SR2) requires fencing off or access restriction but promotes ES supply more than conservation (SR2) and supports the greatest multifunctionality (MF) from the perspective of all the considered groups. Abandonment does not restore the supply of any ES and even incurs ES losses (SR3), because *P. juliflora* consumes significant amounts of groundwater. However, considering economic priorities towards only a priority ES (PF) of fodder for pastoralists, wood products for charcoal producers and ecotourism for tourists would lead these stakeholders to respectively favour livestock production, abandonment or conservation as best restoration options (highest respective PF scores).

1073 **Table 1.** Common ecosystem services of grasslands and indicators of associated ecosystem
1074 structure and function parameters
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| **Ecosystem services** | **Ecosystem structure / function** | **Common indicators** | Scale and means of measurement |
|---|---|---|---|
| Forage production (quantity) | Annual aboveground biomass production | Net primary productivity (NPP), aboveground biomass | NDVI (remote sensing), landscape scale<br>Direct harvesting, local scale |
| Forage production (quality) | Protein content and digestibility | Leaf N content<br>Presence of species of particular nutritional importance (e.g. legumes | Remote sensing at a landscape scale<br>Direct measures at a local scale |
| Forage reliability | Interannual variation in aboveground biomass production | Monitoring of NPP species composition | Remote sensing at landscape scale |
| Other grassland products (e.g. medicinal, food, hunting) | Species of particular interest | Species presence / abundance | Field survey at local scale |
| Biofuels | Woody species of interest<br>Grass species of particular interest (e.g. flammable and high yielding species) | Cover or biomass of species of interest | Direct field measures or remote sensing |
| Species of cultural value | Presence of species of cultural interest | Species presence | Direct measures and local records (e.g. (National monitoring schemes and local surveys) at local scale or regional survey for large areas |
| Aesthetic value | Plant community composition and phenology | Flower cover, flower colour, and presence of ‘unattractive’ species<br>Flowering phenology | Direct survey<br>Phenology can be derived from species list and external databases |
| Biodiversity conservation value | Plant and animal (vertebrate / invertebrate) species | Presence and abundance of species of conservation value | Global Biodiversity Information Facility (GBIF) and national monitoring schemes at larger scales |

| | | | |
|---|---|---|---|
| Regulation of invasive exotics and other undesired species | Invasive exotic species, species of negative pastoral or cultural value | Presence / abundance of undesired species | Direct survey at local scale<br>GBIF and national monitoring schemes at larger scales |
| Global climate regulation | Carbon stocks and carbon cycling processes | Soil respiration and carbon stocks<br>Woody species biomass and vegetation carbon stocks<br>Litter mass / depth | Direct survey at local scale<br>Remote sensing for aboveground stocks<br>Soil sampling and interpolation for belowground carbon stocks and fluxes |
| Maintenance of soil fertility | Nutrient stocks and nutrient cycling processes | Soil nutrient and carbon content<br>Litter mass<br>Soil enzyme activities | Soil sampling and interpolation to required scales |
| Maintenance of soil stability and regulation of erosion | Soil stability in the root profile<br>Erosive flows | Evidence for erosion, bare ground cover and soil organic matter<br>Soil aggregate stability and bulk density<br>Plant rooting profile<br>Direct measures of soil loss / erosive flows<br>Water holding capacity | Field observations or remote sensing to detect erosion<br>Direct sampling and measurement of multiple indicators |
| Regulation of hydrological flows | Soil water retention and flows | Soil texture and bulk density, and soil organic matter content<br>Soil electrical and hydraulic conductivity (rapid assessment methods) | Direct survey and interpolation |
| Regulation of water quality | Retention and transformation of pollutants in soil | Soil physicochemical properties (e.g. texture, pH, CEC)<br>Salinity and water table depth<br>Soil organic matter content and available water capacity. | Direct sampling of soil and water |

| | |
|---|---|
| | Nutrient and pollutant concentrations in freshwater bodies |