SYNTHESIS ARTICLE

The present and future of grassland restoration

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Grasslands contribute greatly to biodiversity and human livelihoods; they support 70% of the world's agricultural area, but are heavily degraded by human land use. Grassland restoration research and management receives less attention than forests or freshwater habitats, although grasslands are critical for sustaining ecosystems multifunctionality and capacity to support biodiversity. In this article, we introduce a Special Issue which considers major trends and prospects in grassland restoration. We identified three key topics: First, restoration must confront widespread seed and site limitations, and new monitoring methods, including remote sensing techniques, are critical for restoration projects. Second, we highlight that restored grasslands typically require ongoing disturbance management and that research is required to determine optimal approaches for implementing this management during restoration. Third, global and regional restoration agendas should be harmonized with site-level goals, and syntheses of current knowledge and research needs must guide grassland restoration across scales. We also identify research gaps to be filled, and challenges which grasslands face in the future: (1) a need for careful target vegetation selection and climate-adaptive restoration; (2) lack of knowledge in dynamics and restoration of several regions and grassland types, including drylands and (sub)tropical regions; (3) increased importance of species arrival sequence, and high stochasticity of species establishment; and finally (4) issues of post-restoration management to guarantee long-term sustainability of restored sites. A new generation of research and restoration projects to bridge these gaps is necessary to mitigate environmental challenges spanning localities to the globe as we commence the UN Decade on Ecosystem Restoration.

Key words: climate change, disturbance management, dryland restoration, global restoration agenda, plant invasion, post-restoration management

Implications for Practice

- Grassland restoration research is needed, including carefully designed experiments and syntheses of current knowledge and research needs.
- .Determining how species arrival and site attributes limit plant establishment will guide effective grassland restoration
- Disturbance management and land use legacies have to be considered during restoration of grasslands, and target vegetation selection should incorporate "climate-adaptive" restoration.
- Global and regional restoration agendas should be harmonized with site-level goals.
- Long-term sustainability of restored sites, and the importance of post-restoration management, should be increasingly considered and integrated into restoration planning.

Introduction

Grasslands are among the largest terrestrial biomes and are hotspots of biodiversity in many regions. These ecosystems cover >25% of the terrestrial earth's surface, with Eurasia alone supporting about 9.3 million km^2 of grasslands (Török & Dengler 2018). In addition to being widespread, grasslands have very high conservation value (Dengler et al. 2014) and provide important ecosystem services including food and fodder, water regulation and freshwater supply, erosion control, pollinator promotion, and carbon sequestration (Bengtsson et al. 2019; Zhao et al. 2020). Yet, grasslands have faced large-scale degradation as a result of agriculture, urbanization, invasive species, climate change, and other anthropogenic factors (e.g. Bakker & Berendse 1999; Walther et al. 2009; Steffen et al. 2015). As we enter the United Nations (2019) "Decade on Ecosystem Restoration 2021–2030", advances to restoration science and practice in grasslands and other ecosystems are critical in order to

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reverse the loss of natural habitats and the decline of biodiversity (Menz et al. 2013; Suding et al. 2015).

Alarming losses both in grassland area and biodiversity have been reported. For example, 50–70% of former grassland area has been destroyed in Europe during the past 30 years (Habel et al. 2013; Dixon et al. 2014). Despite this, grassland restoration research and management have received less attention than forests or freshwater habitats, both in the scientific literature, the media, and among conservation authorities (Overbeck et al. 2013; Temperton et al. 2019). This is supported by a quantitative analysis of recent trends in restoration ecology based on the Web of Science (2011–2020), using the term "restoration" in combination with selected ecosystems (Table 1). Here, most restoration-oriented research focuses on forests, rivers, and wetlands, while grassland restoration contributes less than half as many publications as forests or rivers. There is also some variation in open access publications, which indicates reduced accessibility of research results for practitioners. Only a third of the studies on grassland restoration are open access, compared to higher rates for marine habitats, peatlands, and heathlands. Also, among highly cited publications, those on grassland restoration lag behind research in marine and urban habitats; similar differences are also reflected by steeply increasing publication rates in these other fields. Although in the past decade only moderate attention has been directed to grassland restoration research, the trends are increasing, and some significant papers have been published (see for example Kiehl et al. 2010; Török et al. 2011; Dengler et al. 2014; Helm et al. 2015). Given the ecological significance of grasslands, more research is needed, and the proportion of open access publications should increase to facilitate application of these findings to practice.

To support further advances to the science of grassland restoration, the current special feature was initiated at the SER Europe Conference "Restoration in the Era of Climate Change" (Iceland, 9–13 September 2018) based on the session "Grassland restoration in Europe: Current status and future prospects". The session had broad thematical coverage and demonstrated a wide interest in grassland restoration. At the same time, it indicated a lack of recent syntheses and the need for additional research to direct the science and practice of grassland restoration. In response, we developed this Special Issue, which provides a timely overview of grassland restoration.

In this article, we introduce three key topics in grassland restoration science and practice, based on the contributions to the Special Issue. First, we consider constraints to successful grassland restoration and the measurement of restoration success. Second, we evaluate effects of disturbance management and land-use legacies in restored grasslands. Third, we draw attention to prospects for and limitations of grassland restoration at different scales, evaluate the current status and trends of grassland restoration, and suggest future research directions.

Limiting Factors and Novel Measures of Restoration Success

Meeting global restoration demands will require the development of improved methods to assess and monitor restoration success, and this is certainly true in grasslands (Suding et al. 2015; Cooke et al. 2019). Restoration science and practice have seen tremendous advances during the past decades, yet restoration still broadly fails to regain the biodiversity and other ecosystem attributes present in intact grasslands (Jones et al. 2018). Several papers in this Special Issue advance grassland restoration methods and approaches to monitoring through research conducted in grasslands across a number of countries.

A key theme to these papers is that the re-establishment of target grassland plant species during restoration can be limited by seed arrival and/or barriers to the establishment of arriving seeds (Bakker & Berendse 1999; Török et al. 2011). Understanding the details of these limitations can guide specific restoration practices. For example, seed sowing can help to reestablish plant species that are unlikely to recolonize passively after major disturbances, like cultivation, either because they have limited dispersal capacity or because populations are not in close proximity to a restoration site (Pywell et al. 2002). In turn, arriving seeds may fail to establish due to a variety of constraints such as competitive weedy vegetation, unsuitable soil attributes, or

Table 1. Publication trends in grassland restoration compared to other major habitat types, based on Web of Science (2011–2020, Core collection, 25 January 2021). The search used the term "restoration" in combination with keywords related to important ecosystems and/or habitat types. Shown are the total number of publications within that decade, the percentage of open access and of highly cited papers, and a change index based on the number of publications in the period 2019–2020 divided by 2011–2012. High ranking numbers are printed in bold, low ranking numbers in italic; grassland results in bold-italics.

Study System	Publications	Open Access (%)	Highly Cited (%)	Change Index (2019–2020/2011–2012)
Forest	**10,506**	37	1.01	1.86
River	**8,126**	30	0.53	1.91
Wetland	4,242	*28*	*0.52*	*1.70*
Grassland	*3,766*	*33*	*0.82*	*2.17*
Lake	3,263	30	0.58	1.94
Urban	3,200	34	**1.69**	2.43
Mining	2,231	*28*	0.67	2.36
Marine	1,658	38	**1.93**	**2.90**
Peatland	*594*	**47**	*0.17*	**2.52**
Heathland	*135*	**43**	1.48	*0.82*

temporally variable and unfavorable climatic conditions such as droughts (Brudvig et al. 2017).

Papers in this Special Issue explored various types of seed and site limitation, during tests of restoration methods. Wagner et al. (2021*a*) illustrated the benefits of green hay transfer for reestablishing meadow vegetation in England, particularly for species that were abundant at the donor sites. Thus, reestablishment was most likely when green hay alleviated dispersal limitation. They recommended targeted additions of species not effectively transferred from the donor site, and management of the recipient site to reduce establishment limitations. In a second paper, Wagner et al. (2021*b*) demonstrated similar effectiveness of green hay and seed sowing for re-establishing European meadow vegetation, although effectiveness of both techniques declined when frequent flooding and high levels of soil phosphorus limited plant establishment. Kiss et al. (2021) disentangled the relative roles of seed dispersal and establishment, by combining seed sowing and artificial gap creation, within a species-poor ex-arable grassland in Hungarian lowlands. Sown species established best in gaps as a result of low weed abundance, and began to expand into surrounding non-gap areas within 5 years, illustrating the potential of localized disturbances for broader-scale restoration. Kövendi-Jakó et al. (2021) also showed the importance of seed sowing for re-establishment of sandy grasslands in Hungary. They found, however, that establishment varied among years and argued that repeated seeding could be advantageous under stressful conditions. Grman et al. (2021) considered limitations to sown forb abundance during restoration of North American tallgrass prairies from former agricultural lands. They found that forb abundance is promoted by frequent fire and by sowing forbs at high rates, but limited by competitive C4 grasses, which are also seeded during restoration. These results illustrate the complex interplay between target species groups during restoration and lead to suggestions for how seed mixes can be altered to better promote target plant species. Finally, Řehounková et al. (2021) reported that active reintroduction may not always be necessary for successful grassland restoration. Six years after removing nutrient-rich topsoil from eutrophicated grasslands in the Czech Republic, plant community composition on exposed nutrient poor substrates resembled that of intact reference grassland. Thus, by understanding the limiting factors during community establishment—in this case, excess nutrients and a competitive non-target grass species—they illustrate the potential of passive recovery of target grassland plant species, through natural seed dispersal from nearby populations.

Because of widespread seed and site limitations, monitoring is critical for restoration projects through its role within the adaptive management process. Yet, as restoration efforts scale up to meet global demands, new methods may be needed. For example, Blackburn et al. (2021*a*) evaluated the utility of monitoring a U.S. prairie restoration using an unmanned aerial vehicle. They showed that this approach could predict multiple attributes of restored prairie, including graminoid cover and dry biomass, illustrating the potential of remote-sensing tools for scaling monitoring capacity as restoration projects expand in size.

Disturbance and Land-Use Legacies in Restoration

Grasslands are disturbance-driven ecosystems (Collins et al. 1998; Lunt & Morgan 2002; Fynn et al. 2004; Koerner & Collins 2014). Disturbances promote plant diversity by reducing biomass of dominant (mostly) grasses; thereby increasing light availability for sub-ordinate species to recruit and persist (Morgan 1999, 2015; Borer et al. 2014). Optimal disturbance regimes tend to be context-dependent and consider aspects of intensity, frequency, timing, and extent of disturbance. This information is often available for remnant grasslands (e.g. Collins et al. 1998). Restored ecosystems, however, may contain new assemblages of species, and novel abiotic conditions, including those driven by historical land use. Here, disturbance management is complicated because management in reference sites might not be best suited to restored assemblages. Hence, restoration management requires additional research, and understanding of the current assemblages, seed banks, weed invasion, land-use legacies, and the effects of alternative disturbances on current conditions.

Key issues explored in the Special Issue include grazing (Blackburn et al. 2021*b*), fire, mowing, land-use legacies (nitrogen deposition, weed invasion), soil seed banks (Valkó et al. 2021), and abandonment of disturbance (Hernandez et al. 2021; Price et al. 2021; Reis et al. 2021; Valkó et al. 2021; Blackburn et al. 2021*b*). Although restored grasslands have a disturbance requirement, optimal management may differ in restored grasslands from reference sites due to differences in species composition, land-use legacies, weed invasions, or other factors. The papers in this Special Issue highlight the importance of experimenting with different approaches to promote target species and to reduce non-natives in restored grasslands. This will become increasingly important as global-change processes alter abiotic conditions, requiring forward thinking planning (Wilsey 2021).

Generally, some disturbance is necessary in restored grassland assemblages to promote native target species and reduce exotic species. For example, Reis et al. (2021) reported that mowing promoted native grassland species and eliminated a woody weed (in combination with herbicide), whereas dense woody cover developed in unmown plots. Assis et al. (2021) also found disturbance was required to reduce exotic grasses in Cerrado grasslands. Here, the optimal management to reduce exotics and increase native richness was hoeing, and though other techniques reduced exotic cover, they did not meet the restoration goal of also increasing native species richness and cover. In restored grasslands, Valkó et al. (2021) demonstrated that ongoing disturbance management was needed to maintain cover of sown target species and reduce weeds. Here, remnant grasslands were less dependent on management, confirming differences in restored compared to remnant sites.

Some authors considered which disturbance type had the best outcomes in restored grasslands. For example, Hernandez et al. (2021) looked at fire (one-event) and grazing effects on native forb recovery in invaded serpentine grasslands. They found that fire (a non-historical disturbance) promoted native forb recovery, but ongoing disturbance was required to promote

diversity. In this case, grazing performed a similar role in promoting native forbs and reducing non-native cover (through reductions in litter cover). Price et al. (2021) reviewed switches in disturbance type in temperate grasslands in Australia and detected persistent land-use legacies of introduced stock grazing (non-historic disturbance). Removal of this type of grazing and reintroduction of fire (historical disturbance) had limited effects on native richness. Blackburn et al. (2021b) found bison dietary preferences differed in restored tallgrass prairies compared to remnants, with native forbs being a larger component of their diet. They caution that bison reintroduction may have unintended consequences, as grazing is typically used to reduce grass biomass and promote native forbs. Recommendations were made to account for dietary preferences at the planning stage when considering seed mixes.

Muted responses to the management of restored grasslands may be due to propagule availability; hence, grasslands are typically seed-limited (Seabloom et al. 2003). For example, Reis et al. (2021) reported that the composition of mown restored grasslands was most similar to reference sites in sites that had greater propagule availability of target species. Hernandez et al. (2021) suggested recovery of invaded serpentine grasslands with disturbance management was due to the presence of natives in the soil seed bank in sites with a shorter period of invasion than in other regions. Price et al. (2021) concluded that grazing-sensitive species are likely lost both above- and belowground with a long legacy of stock grazing, and fragmentation reduces dispersal opportunities. Valkó et al. (2021) found that the seed bank had limited potential to maintain richness of restored grasslands and tended to be dominated by weeds. Hence, a common message is that disturbance management alone is unlikely to lead to positive outcomes if native seed banks are exhausted.

Many of the papers in this Special Issue highlight the importance of long-term management and monitoring to determine optimal management strategies. In most cases, abandonment of management negatively affected restored grasslands compared to grazing, fire, and/or mowing (Hernandez et al. 2021; Price et al. 2021; Reis et al. 2021; Valkó et al. 2021). Hence, restoration projects should ensure that resources are available for ongoing management at the planning stages. Additionally, monitoring needs to be long term, because short-term monitoring may lead to different conclusions about management efficacy. For example, Reis et al. (2021) found that mowing was an effective post-restoration management technique in the long term, while short-term monitoring (3–5 years) would have concluded a failure of mowing.

Synthesis to Guide Grassland Restoration Across Scales

By organizing current knowledge, identifying research gaps, and proposing new research directions, synthesis forms a critical aspect of the research process. At no time has this been more pressing in restoration than the present, when restoration scientists and practitioners are being called upon to solve environmental challenges across scales. Restoration actions need to

counteract local-scale habitat degradation, but also sustain natural migration and dispersal networks across the landscape (Suding et al. 2015). At even larger scales, restoration actions are increasingly advanced as nature-based solutions to mitigate climate change effects (Brancalion & Holl 2020). This can sometimes result in conflict between the restoration goals at multiple scales. For example, global-scale agendas, which often focus heavily on tree planting, may translate poorly to meet the needs of regional or local-scale conservation efforts or needs (Temperton et al. 2019). Such conflicts might be mitigated if global and regional restoration agendas are harmonized with site-level goals (Brudvig 2011). Syntheses of current knowledge and research gaps are needed, to guide grassland restoration across scales, to support the next generation of research.

The papers of Buisson et al. (2021a, 2021b) and Wilsey (2021) identified several research gaps to be filled and challenges which grasslands face in the forthcoming decades. These include the (1) need for careful target vegetation selection and "climate-adaptive" restoration; (2) lack of knowledge on the dynamics and restoration of several regions or grasslands types; (3) increased importance of the species arrival sequence and high likeliness of stochasticity of species establishment; and, finally, (4) issues of long-term sustainability of restored sites/habitats in the form of post-restoration management.

Through two review papers, Buisson and colleagues evaluate areas of focus and needs for grassland restoration. Buisson et al. (2021a) stressed that the restoration of dryland ecosystems, which are predicted to increase in area owing to desertification, is seriously threatened by the establishment limitation of their species by high temperature and drought especially in the summer periods, and also missing or low-density seed banks of characteristic species. This underlines the necessity of setting realistic goals for target selection in restoration (Török & Helm 2017). In their second review, Buisson et al. (2021b) indicated that most research has been conducted on restoration of temperate grasslands, whereas tropical grasslands have received much less attention. Scientific knowledge is especially limited on how to restore biodiverse grasslands in tropical and subtropical regions and can even lead to misunderstandings or misconceptions (see also Silveira et al. 2020). To restore the biodiversity of these grasslands, prescribed fires, grazing management, wild herbivores' grazing, tree cutting, shrub removal, and invasive species control are key issues. Monitoring should be evidence-based to assess desirable structure, composition, functioning, resilience, and stability of grasslands and savannas.

Wilsey (2021) identified several areas of need in grassland restoration research, several of which were also noted by Buisson et al. (2021a, 2021b). First, Wilsey (2021) pointed out that setting pre-industrial vegetation as a restoration target of our actions is not feasible. This is for several reasons: (1) altered site conditions and land use, and modified landscapes with marked effects on dispersal and establishment in most regions (Török et al. 2020); (2) biological invasions and multiple threats imposed by climate change (Wilsey 2021); and (3) increasing stochasticity means that restoration success may depend on years with particular rainfall amounts or patterns, or on the differences in reproductive and establishment success of particular

target plant species between years (Buisson et al. 2021*b*). This also highlights the importance of the sequence of arrival of plant species, so-called priority effect in restoration (Weidlich et al. 2021; Wilsey 2021).

Together, the papers in this Special Issue illustrate the state of the art in grassland restoration. From local-scale experiments to resolve processes limiting restoration success, to tests of novel restoration approaches, and to global syntheses, these papers illustrate how restoration can best promote grassland biodiversity and ecosystem functioning. At the same time, they point to key research needs and help to set the agenda for a new generation of grassland restoration, as we enter the UN Decade on Ecosystem Restoration to mitigate environmental challenges spanning localities to the globe.

Acknowledgments

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