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RESEARCH ARTICLE

Proposing a social-ecological framework for successful grassland restoration in Germany—an overview and insights from the *Grassworks* project

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Abstract

Introduction: Bending the biodiversity curve and meeting international commitments like the Kunming-Montreal Agreement and the EU Nature Restoration Law require scaling up ecological restoration across spatial, temporal, and societal dimensions. Achieving this depends on a strong scientific evidence base and synthesis of effective practices from both ecological and social perspectives.
Objectives: The *Grassworks* project investigates factors influencing grassland restoration success in Germany by integrating ecological, socioeconomic, and social-ecological perspectives.
Methods: We assessed previously restored grasslands across three regions along a north–south gradient in Germany, comparing them to reference sites. A stratified design evaluated restoration outcomes based on methods, past land use, management, governance, finance, and time since intervention. We analyzed vegetation, pollinators, soil, and economic performance while considering landscape configuration. Social-ecological aspects, including stakeholder values, knowledge exchange, and decision-making networks, were also examined. A Real-World Laboratory approach integrated ex ante and ex post evaluations, demonstration sites, and co-created restoration activities.
Results: We propose a replicable, adaptable framework for social-ecological restoration, synthesizing key ecological, economic, and social dimensions to support continuous learning and adaptive management, facilitating more effective and scalable restoration practices.
Conclusions: Drawing from the *Grassworks* project, this research provides insights to inform and guide future large-scale restoration efforts, promoting a holistic and evidence-based approach to social-ecological restoration worldwide.

Implications for Practice: Legal framings such as the EU Nature Restoration Law or the Kunming-Montreal Biodiversity Agreement now require a strong evidence base for scaling up restoration initiatives on the ground. Applying a social-ecological lens to what constitutes success in restoration, as well as integrating findings across regions contributes significantly to providing such a science and practice-driven evidence base. The social-ecological and landscape-level approach used in *Grassworks* can be replicated in other large-scale restoration research to connect scientific findings more strongly with policy and practice. Such an integrative approach demands frequent communication and a common language as well as trust between scientists from disparate fields of enquiry (across natural and social sciences). This requires a high level of openness as well as time. However, the communication and time investment are rewarded with more generalizable, broad, robust, and integrative outcomes.

Key words: ecological assessments, governance, real-world laboratory, restoration outcomes, social-ecological interactions, stakeholder collaboration

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Introduction

Species-rich grasslands worldwide are under threat of degradation despite grasslands providing a wide array of different ecosystem functions and therefore also benefits to people (Bengtsson et al. 2019; Bardgett et al. 2021) and covering more than a third of terrestrial land globally (Squires & Jürgen 2018). As the UN Decade on Ecosystem Restoration unfurls, scaling up restoration activities (Shackelford et al. 2013; Perring et al. 2018) represents one of the main opportunities and challenges. Developing a strong evidence base for best practice in restoration will form a key component of scaling up.

Restoration activities on grasslands have, until recently, mainly focused on achieving ecological targets such as increasing plant diversity (Kirmer et al. 2008; Helm et al. 2015; Hess et al. 2020; Shackelford et al. 2021b) or more recently improving biotic interactions such as plant–pollinator networks (Montoya et al. 2012; Traveset et al. 2013). Social, political, cultural or economic factors have so far received limited attention in the assessment of restoration success (Wortley et al. 2013; Fernández-Manjarrés et al. 2018; Elias et al. 2021; Tedesco et al. 2023), despite evidence that ecologically successful projects are often influenced by social framings, such as the acceptance of restoration outcomes (Pfadenhauer 2001), cost considerations (Waldén & Lindborg 2018), governance, implementation and protection (Canessa et al. 2023). Although research on payments for ecosystem services in grasslands has gained traction, and result-based payments represent a method to evaluate restoration success and economic incentives (Huber & Finger 2020), integrative approaches that combine economic with ecological and social-ecological factors remain rare. Social framings can influence restoration success, as seen in wildflower meadows threatened by urban development or tree planting failing due to poor timing (Messier et al. 2015). At the same time, these projects or initiatives significantly affect the lives of individual people, influencing the development of local economies, the configuration of governance structures, and the cultural connections to restored landscapes. The extent to which stakeholders—such as farmers, landowners, conservationists, local community members, policymakers, and restoration practitioners—are included in (i) restoration actions, decision making processes, levels of participation and power dynamics, (ii) the extent to which the connection to nature motivates practitioners and stakeholders to restore grasslands, and (iii) the socioeconomic and policy framing of activities can and likely does significantly influence the success of restoration. These aspects of restoration have been understudied (see Broeckhoven & Cliquet 2015; Martin 2017; Buckingham et al. 2021; Fischer et al. 2021), while the awareness of the importance of such social factors increases. Studies that include equal focus on the ecological and the social dimensions, as well as the interface between the two, are so far practically non-existent (hence the appeal in Fischer et al. 2021, to perform such integrative research in the UN Decade on Ecosystem Restoration; see also Tedesco et al. 2023).

In the interdisciplinary and transdisciplinary project *Grassworks*, we aim to holistically fill this research gap by investigating under what conditions grassland restoration is successful, explicitly including ecological, social-ecological as well as socioeconomic variables. In large parts of Europe, species-rich grasslands are among the most threatened habitat types, with <10% of these grasslands that are protected under EU law being in a favorable condition, and 75% showing negative biodiversity trends (Wesche et al. 2012; Dengler et al. 2014). Studies in Germany have highlighted not only the extent of plant species loss, but also the specific types of species being lost, with the majority being those adapted to open ecosystems, particularly grasslands (Jandt et al. 2022; Staude et al. 2023). Therefore, restoring species-rich meadows and pastures, as emphasized in the recently ratified EU Nature Restoration Law (https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-law_en), is highly likely to deliver a substantial societal return on investment (De Groot et al. 2013; Shipley et al. 2024).

In the *Grassworks* Project (https://grassworksprojekt.de/en/), we address the central research question: "What leads to success in grassland restoration in Germany?" by exploring ecological, socioeconomic, and social-ecological dimensions. Our integration of these dimensions (sensu Fischer et al. 2021) is grounded in the insights and methodologies developed within the project. Through this comprehensive approach, we aim to establish a robust evidence base to inform and guide future social-ecological restoration efforts. The project integration focuses on three regions in Germany, thereby providing a latitudinal gradient from North to South. As a backdrop to our findings, we acknowledge the well-documented latitudinal biodiversity gradient in European grasslands, with higher biodiversity observed in southern regions (Dengler et al. 2014). In the *Grassworks* project, we consider this expected gradient as a contextual baseline for exploring restoration success, while recognizing that regional differences often outweigh these broader macroecological patterns (Socher et al. 2013). We explicitly selected a wide range of grassland habitats to ensure the outcomes are both more generalizable and more easily transferable to other grassland systems.

This publication has two main goals: first, it provides an overview of the approach and methods used to assess ecological, social-ecological, and socioeconomic restoration success across three different regions in Germany (North, Center, South). Secondly, given the extensive efforts to standardize and improve comparability of the measurements across restored sites and regions, we provide insights into the decision-making and reflection processes that underlie the experimental design and approaches taken. This includes the main rationale of the research design, with the aim of allowing other researchers to replicate or refine and adapt the design further and fostering continuous improvement by advancing the evidence base for restoration success. This highlights the critical importance of integrating social and economic dimensions into restoration efforts and success, thereby recognizing the interdependence of ecological, economic, and social phenomena.

Such projects are directly relevant to policy and practice as they help identify intervention points that target key social-ecological transformations (see "leverage points" in Abson et al. 2017) and guide future cost-effective strategies to maximize the likelihood of restoration success.

Methods

From a social-ecological perspective, the most successful grassland restoration can be defined as a process that considers ecological components, social aspects and socioeconomic facets, as well as the improved benefits to people. Ecologically, we perceive grassland restoration as successful when as many native grassland species as possible are established, leading to higher alpha, beta, and gamma diversities as well as improving vegetation structure and ecosystem functions (in other words enabling "ecological complexity", see Wortley et al. 2013). Restoration projects increasingly also consider the forb–grass ratio (that is linked to multitrophic interactions) as a key metric of restoration success (Bucharova & Krahulec 2020; Nerlekar et al. 2024). Reflecting these principles, our project included the assessment of species diversity and vegetation structure, including the forb–grass ratio, to evaluate restoration success more comprehensively.

Given the acceleration of global change as well as the need to include a wider range of human-related outcomes, restoring ecosystem functions and services is an emerging focus of social-ecological restoration (Funk et al. 2017; Carlucci et al. 2020). From a social perspective, successful restoration also improves human–nature connections (that integrate diverse values, practices and knowledge) and achieves a balance between natural processes and human needs, combined with inclusive governance and effective economic incentives across temporal and spatial scales (Fischer et al. 2021; Tedesco et al. 2023). Finally, these factors contribute to the resilience of the system, so it is sustained for future generations (Lyons et al. 2023).

Restoration is very likely to deliver diverse benefits to society, but it is inevitably connected with costs for initial restoration and maintenance that are often borne by farmers and landowners (Zerbe 2023). From a socioeconomic perspective, restoration success translates at the societal level into positive social net benefits or high benefit–cost ratios, indicators that require all costs and benefits to all members of society to be measured in monetary terms and are hardly calculated (for an exception, see De Groot et al. 2013). Cost-effectiveness measures might be used if benefits, like species richness, are not measurable in monetary terms (Knight & Overbeck 2021). At the site or farm level, profitability, cost coverage, employment and income, and long-term maintenance perspectives are typical indicators of successful restoration (Waldén & Lindborg 2018; Asma Ben-Othmen et al. 2023).

The *Grassworks* approach combines a post hoc assessment of already restored sites with real-world laboratories (RWLs) in each of the three study regions. This follows recommendations in Fischer et al. (2021) for a research agenda for social-ecological restoration in the UN Decade on Ecosystem Restoration. Our central hypothesis is that restoration success relates to the extent to which both ecological complexity (encompassing biodiversity, vegetation structure, ecosystem functions) and social engagement (stakeholder diversity, inclusion) are considered in the restoration process. We hypothesize that the higher ecological complexity and social engagement are, the higher the restoration success will be (Fig. 1). To maximize the potential for restoration success, *Grassworks* is creating an integrative framework that can be used to develop potential scenarios for how ecosystem multifunctionality can be enhanced through the process of grassland restoration.

Given the centrality of stakeholder perspectives in our study, we also reflect briefly on the use of this term. We are aware of recent critical discussions on the use of the term stakeholder, particularly regarding its colonial origins and potential to reinforce exclusionary narratives in participatory processes (Reed et al. 2024). These debates emphasize the importance of reflexive, inclusive language that foregrounds agency and equity in research and decision-making. In this manuscript, we decided to keep the term stakeholder because it remains widely used and understood in the German context and aligns with the terminology used in the RWL settings and policy frameworks we examine. We use it specifically to refer to individuals, groups, or organizations that have an interest in, or are affected by, restoration efforts. Nonetheless, we acknowledge the limitations of this term and align with broader efforts to critically reflect on language in research and practice.

Results

To assess the success of restoration projects, we used a landscape-scale "natural experiment" design with an assessment of ecological, economic and social attributes of restoration in 187 sites across three different regions in Germany (Fig. 2).

The Northern study region is economically (measured in GDP per capita) and ecologically in the median range (related

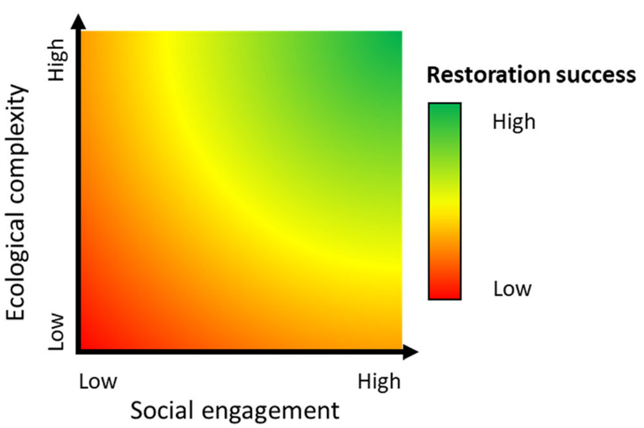


Figure 1. Our central hypothesis is that the overall social-ecological success of restoration relates to the extent to which both ecological and stakeholder complexity are considered in the restoration process. We hypothesize that the higher the ecological complexity and social engagement (stakeholder diversity/inclusion) are, the higher the restoration success will be. Our combination of ecological, social-ecological, and economic data within *Grassworks* allows us to test this hypothesis. The success of restoration is shown as a sequence of colors, ranging from low (red) to middle (yellow) and high levels (green), the latter can only be achieved with high values on both social and ecological axes.

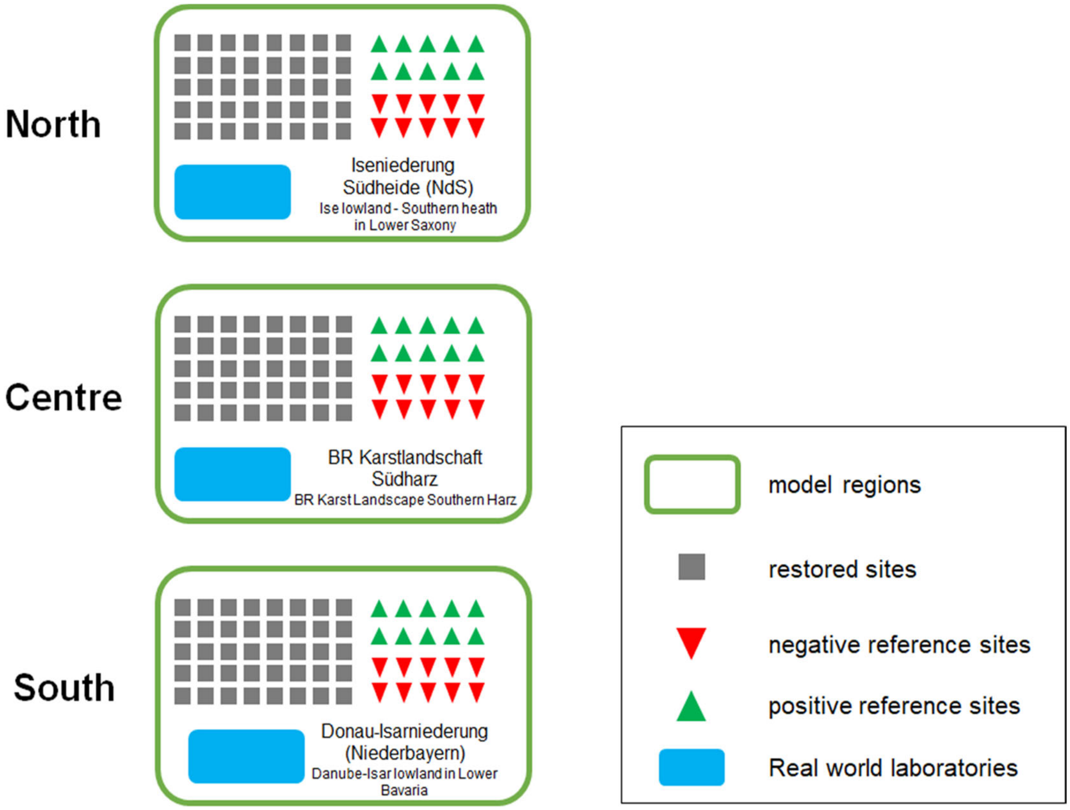


Figure 2. The *Grassworks* research approach for assessing grassland restoration success using a natural landscape experiment approach for the post hoc sampling and RWLs. We compared three regions from north to south in Germany. Within each region we did a post hoc assessment of approximately 40 already restored grasslands as well as 10 positive and 10 negative reference sites (see Table 2 for exact details of numbers of sites per region and category). In addition, we set up one RWL per region, where in situ restoration with local stakeholders was co-designed and performed (for the North and the Center) and an online forum was established in the South. BR = biosphere reserve.

to plant species richness) compared to the whole of Germany. The Central region combines good ecological quality with lower economic strength, and the Southern region combines strong economic performance with above-average ecological quality For both the Center (Saxony-Anhalt) and South (Bavaria), all *Grassworks* sites lay within one federal state, whereas for the North we sampled in four different federal states, namely Lower Saxony, Schleswig Holstein, Hamburg, and northern parts of Saxony-Anhalt, each with partially varying agri-environment and impact mitigation schemes, as well as differing economic conditions.

Post Hoc Assessment: Study Design and Landscape Experimental Setup

We developed a post hoc assessment to provide a holistic analysis of factors that affect grassland restoration success in Germany, collecting ecological, social-ecological, and economic data in grasslands already restored by local stakeholders in the three regions (Fig. 2). Data were collected over two growing seasons, spanning 2022 and 2023. In addition to measuring local site conditions, we used remote sensing data to assess the surrounding landscape around the restored sites by delineating different land use types (grassland, arable land, forest, settlements, and others) and compiling plant species richness for each land use type within a 300 m radius of each restored site.

Overall, we sampled 121 restored grassland sites, as well as 33 negative and 33 positive reference sites across Germany, totaling 187 sites (with around 40 restored sites plus 10 positive and 10 negative sites per region; Table 2). We included dry, fresh and moist to wet grassland types (excluding only grasslands on peat soils). Target EUNIS habitat types (referenced in Chytrý et al. 2020) were semi-dry calcareous grassland (R1A), pastures (R21), lowland hay meadows (R22), moist or wet eutrophic meadows (R35), and moist or wet oligotrophic grasslands (R37). The grassland sites represent a wide gradient of different conditions in terms of their ecological and social-ecological characteristics. Our design aimed to increase transferability of results across Germany and to similar temperate conditions. In line with many ecological restoration projects, we compared variables measured in restored sites with positive reference (non-degraded) as well as negative (degraded) reference sites (sensu Zedler 2007; Wortley et al. 2013; see Fig. 2, also Boxes 1 and 2 for a reflection on the process of site selection). This approach allows a comparison of the variability of factors that affect restoration success within and between three larger

Box 1 Reflections on selecting restored sites and what constitutes a restoration method within the post hoc approach.

When selecting sites in the three regions as part of our natural landscape experiment approach (Fig. 2) we decided to take the availability of different grassland types in the real landscape within our three larger regions (North, Center, South) into account, and did not stringently balance every factor that we considered important for restoration outcomes (see Tables 1 and S2 for more details). This particularly applied to some regionally more specific factors that are affected by local climate (e.g., prevalence of wetter grasslands in the North compared to Central or Southern Germany), cultural and historical land use (e.g., less grazing in the southern region than in the North or the Center), with sites in the South concentrated around the lowlands surrounding Munich in Lower and Upper Bavaria.

Nevertheless, when selecting sites, we strove to balance out the number of sites per level as much as possible for the following main factors: hydrology, time since restoration intervention, restoration method, previous land use, and current management (Tables 1 and S2). A certain number of factors were deemed potentially important but too difficult to adequately assess prior to starting fieldwork. Here, the information was obtained later and included the full variety of funding instruments, whether a grassland site was located in a nature conservation area or not, and different soil preparation approaches before restoration. We found restored sites via our networks of local contacts, previous collaboration partners in conservation practice, local conservation authorities, and NGOs, and through a snowballing effect among these stakeholders.

The question of whether management (grazing or mowing) constitutes a restoration method (as opposed to direct harvesting or sowing or seeds) engendered a lively debate. While all grasslands that are not on extremely wet or dry sites, require some form of disturbance (grazing or mowing) to remain grasslands and not go through successional processes, one form of ecological restoration of grasslands includes adapting such grazing or mowing management. As such, we decided to include a combination of mowing and grazing as one of the restoration methods in our post hoc analysis of the restored sites.

regions and should significantly increase the predictive power of such studies for restoration measures (sensu Brudvig 2017). The final randomized stratified design included the following main factors that can influence restoration outcomes, that is, restoration method, age since main restoration intervention, previous land use, and current management (grazing or mowing, or a combination of both).

Post Hoc Assessment: Ecological Variables and Field Sampling

Each site was sampled once per year using a space-for-time approach to assess vegetation, soil chemistry, and texture. At each site, a 200-m transect (5 m wide) was set up and marked using GPS coordinates, with an accuracy of 0.01 m (Fig. 3). Each transect was separated into four 50-m sub-transects that were sampled for vegetation, soil, and insects.

Vegetation: within each 50-m section, 4 m^2 (2 m × 2 m) vegetation plots were surveyed positioned at points derived at random along the 50-m stretch, with the minimum distance of 5 m from the end of the transect), giving four plots per site and a total vegetation sampling area of 16 m^2 (Fig. 3). Within each vegetation plot we assessed species presence as well as cover using a modified Braun–Blanquet scale (see Table S1 for details). Additional plant species were recorded for a maximum of 1 hour on the entire 1,000-m^2 transect. Additionally, vegetation height was measured four times per year using a drop disc along the 200-m transect. To assess the percentage of area covered by flowers, overhead photos of the vegetation (with the camera at a height of between 1 and 1.5 m) were taken within the 4 m^2 quadrants during the insect surveys and subsequently analyzed in the lab.

Soil: At each site in March or early April at each vegetation plot, we took soil samples (pooled from six soil cores, 20 mm diameter) that were further pooled into one sample per site and analyzed for total soil organic carbon (SOC), total nitrogen content, pH (both actual and potential pH), and soil texture as well as microbial biomass (carbon based). Additionally, soil bulk density was measured at two locations per site, to enable future assessment of carbon sequestration over time. Soil and bulk density samples were taken at two depths: 0–10 and 10–30 cm. These depths are commonly sampled across Germany, allowing national and international comparisons in line with standard synthesis project procedures in Germany (Poeplau et al. 2020).

Insects: Butterfly and wild bee sampling was done monthly, four times per site from May to August along the 200 m transect (width: butterflies 5 m, wild bees 2 m) when weather conditions were suitable (see Fig. 3). Butterflies were counted using the Pollard Walk method (Pollard 1977), and wild bees were collected by sweep netting for 5 minutes within each 50-m sub-transect section, resulting in a total of 20 minutes of observation per transect. Additional butterfly and wild bee species were collected by conducting two further 5-minute random walks across the entire site. Butterflies were identified to species level in the field and wild bees were collected and identified in the laboratory. This overall ecological and biophysical sampling constitutes an elaborate range of variables assessed using standardized methods consistently applied across all three regions.

Post Hoc Assessment: Surrounding Landscape, Production Economics, and Social-Ecological Dimensions

In addition to the ecological variables measured within all the sites, we assessed the surrounding landscape using land-cover

Box 2 Reflection on selecting positive and negative reference sites.

Ecological restoration often compares the outcomes of a restoration intervention to a contemporary positive reference site. The contemporary positive reference generally represents the desired ecosystem state, usually with respect to plant species composition and diversity, vegetation structure, and ecosystem functions, as well as sometimes the forb to grass ratio in grassland restoration. The extent to which a restored site is converging on the plant species compositional space of a positive reference (or not) in multivariate analyses conventionally forms part of the method to monitor the success of restoration projects (e.g., Choi et al. 2008). Comparing restoration outcomes to negative (degraded) reference sites is much less commonly done (Shackelford et al. 2021a) but can frame the overall trajectory comparisons effectively (Wortley et al. 2013). Drivers of degradation in species-rich grasslands are intensive land use (such as fertilizing, or mowing more than twice a year) or abandonment and subsequent shrub and tree encroachment (Shipley et al. 2024). For an overview of the use of contemporary, historical, or future reference sites across local to regional scales, see Shackelford et al. (2021b).

In *Grassworks*, we used contemporary and local reference sites, both negative and positive. We chose classical contemporary positive reference sites based on their vegetation composition and diversity since these were more easily available and since data on other attributes of the reference sites (e.g. functions, functional traits, ecosystem functions and services) were too sparsely available (see Funk et al. 2024 on this topic). One of our main aims was to compare the restoration outcomes with positive and negative reference sites and thus assess how the inclusion of negative references affects the visualization of restoration success. To categorize what constitutes a positive reference site, we used both EU and German state-level information on vegetation of different grassland habitat types including grasslands within the EU Flora Fauna Habitats Directive and Natura 2000, but also regional environment ministry databases (e.g., NLWKN 2023; https://www.nlwkn.niedersachsen.de/vollzugshinweise-arten-lebensraumtypen/vollzugshinweise-fuer-arten-und-lebensraumtypen-46103.html). In addition, we used the following regional sources of habitat information (von Drachenfels 2021), regional lists of donor sites (Spenderflächenkataster: https://www.spenderflaechenkataster.de/startseite), Landesamt für Umweltschutz (LAU) in Saxony-Anhalt (LVermGeo n.d.; FFH-Lebensraumtypen in appendix I of Fauna-Flora-Habitat-Directive, Directive 92/43/EWG; https://www.lvermgeo.sachsen-anhalt.de/de/gdp-geodaten-karten.html), and Biotopkartierung Bayern (https://www.lfu.bayern.de/natur/biotopkartierung/index.htm).

Our approach has the strength that our restored and reference sites represent a gradient of restoration intensity across three different regions in Germany. The challenge, however, consisted of finding both positive and negative reference sites. Initially, we had hoped to be able to pair the restored sites with one negative and one positive reference site each, but it was not possible to obtain enough negative or positive reference sites from our network of stakeholders. Overall, finding restored sites proved easier than finding positive reference sites, with negative reference sites being the hardest to find. Presumably, good quality positive reference sites are now rather rare, and for the negative references, it seems that many stakeholders and organizations were reluctant to provide us with degraded, low diversity grassland sites, which was an interesting realization during the process of site selection during the planning of the post hoc site analysis.

datasets from authorities (Table S3), satellite images as well as on-the-ground assessment of plant species richness within a 300 m radius around the sites (local ground truthing of all higher plant species present). These data allow us to also explore the relation between the surrounding landscape and restoration outcomes, including assessing the possible role of available extensive grassland area in the surrounding landscape, landscape diversity (the number and share of different land use components), and landscape configuration. We created landscape data for a radius of 2 km around each site.

Land-cover datasets were aggregated and checked for missing objects and errors using the digital orthophoto with 20-cm resolution (DOP20) (Bundesamt für Kartographie und Geodäsie 2023). For example, we digitized missing landscape features such as hedges and ditches with at least 2 m width (Table S3). In addition, we used the crop type and mowing events raster layers by Blickensdörfer et al. 2022 and Schwieder et al. 2022, respectively, to calculate the area of extensive grassland in the surrounding and crop-type diversity, as well as the amount of available pollen and nectar and pesticide use (Hellwig et al. 2022). In total, we collected and produced data for 1916 km^2. All geographical data were processed in R (version 4.1.2; R Core Team) with the packages: sf (Pebesma & Bivand 2023), terra (Hijmans et al. 2024), osmdata (Padgham et al. 2017), and the tidyverse (Wickham et al. 2019). Corrections were made in QGIS (version 3.28.0-Firenze).

All sites were incorporated into a production-economics assessment using online questionnaires to gather data on initial restoration efforts and current management practices. This assessment aimed for an in-depth cost-coverage and cost-effectiveness analysis of the measures implemented throughout the initial restoration and management phases. The questionnaire on initial restoration (implemented in the software Unipark, Tivian 2024) included questions on the timing and methods of restoration, including soil preparation, seed introduction, initial maintenance and financing. A questionnaire on current management requested information on type of management, timing, utilization of forage, maintenance measures, and financial support for the year 2022. Relevant stakeholders (farmers, administrative, and NGO personnel) were approached

Table 1. Overview of site and management variables used as stratification factors for the landscape-scale post hoc analysis of restoration success. These site and management variables and their levels were developed using expert knowledge within the consortium as well as a survey distributed to restoration stakeholders across the three regions (51 people filled out the survey about a total of 183 sites, including reference sites). Wherever possible we tried to have similar numbers of sites per level within a region.

Variable	*Level*			
Site				
Aim of restoration	Species rich	Erosion control	Carbon storage	Landscape connectivity
Hydrology	Dry	Fresh	Moist	
Previous land use	Grassland	Arable land		
Time since restoration	1–5 years	6–10 years	>10 years	
Management				
Site preparation	Creation of open soil	Nutrient reduction	Shrub removal	
Restoration measure	Cultivar seed mix	Regional seed mix	Direct harvesting	Management adaptation
Current management	Grazing	Mowing	Grazing and mowing	

to fill out questionnaires online or on the phone from January 2023 to March 2024. Furthermore, we developed a broader social-ecological assessment based on stakeholder's perceptions of the type of restoration performed, the restoration goals and success, and the effect of the social-ecological context. Regarding the type of restoration, we explored key aspects such as the degree of stakeholder involvement, the type of knowledge applied, or the approach and practices used. We also explored the perceived level of priority as a restoration goal and the achieved success of aspects related to plant and insect diversity, the degree of human–nature connections, livelihood opportunities or social cohesion, among others. Within the social-ecological context, we assessed if factors such as the climate conditions, land use practices, stakeholder engagement or people's values toward restoration were perceived as enhancers or inhibitors of the restoration process. The perceptions were collected through an online questionnaire that was sent to stakeholders with different roles and degrees of involvement in the restoration process. We used multivariate analyses to identify archetypes of restored grasslands based on restoration type, prioritization of goals, perceived success, and the influence of the social-ecological context. These archetypes summarized stakeholder perceptions of the restoration process and the balance between ecological and social success, providing a complementary perspective to ecological field data and production economics analyses. Alongside interviews with restoration stakeholders, we surveyed the public across Germany to assess the value of grassland restoration. Our framework highlighted the diverse values driving stakeholder engagement, emphasizing their role in fostering inclusive and effective restoration efforts.

RWL as a Transdisciplinary Approach

At the heart of *Grassworks*' social-ecological research component are the RWL. Working at the interface between science, practice, and local communities, RWLs are becoming more widely used for exploratory and transdisciplinary research approaches (Schäpke et al. 2018; Bergmann et al. 2021). The main function of the RWLs is to act as newly structured forms of cooperation and collaboration between scientific and social actors, as well as open spaces for research, social learning and co-design, where new ideas can be thought through in a transdisciplinary and experimental way, thereby initiating transformation processes (Schäpke et al. 2024). As part of our project, the RWLs provided an experiential environment where we engaged with various stakeholders in shared learning, co-creation, and reflection on their practices and future perspectives related to grasslands. It is important to note that RWLs are inherently

Table 2. Number of sites sampled across the three regions in the post hoc assessment in *Grassworks*, showing the number of restored, positive and negative reference sites sampled per region (187 sites in total) in the first section of the table. The second section shows values for the restored sites (without references sites) for each level of each stratification factor (restoration method, previous land use, and age since restoration) giving a total of 122. It took two growing seasons to measure all sites (2022 and 2023). CuS, cultivar seed mixture; DiH, direct harvesting; MgA, management adaptation; ReS, regional seed mixture.

Variable	*North*	*Center*	*South*	*Subtotal*
Site type				
Restored	40	41	40	121
Positive	11	12	10	33
Negative	10	13	10	33
Current Management				
Mowing	35	32	57	124
Grazing	12	17	1	30
Both	13	10	2	25
No	1	7	0	8
Subtotal (all sites)	61	66	60	187
Restoration method				
MgA	8	14	0	22
DiH	11	4	25	40
ReS	10	17	11	38
CuS	11	6	4	21
Previous land use				
Grassland	13	15	13	41
Arable land	27	26	27	80
Age since restoration (years)				
<5	18	12	9	39
6–10	11	11	6	28
>10	9	15	17	41
NA	2	3	8	13
Subtotal (restored sites)	40	41	40	121

Figure 3. Approach to assess ecological parameters at each of the restored or reference sites in the post hoc assessment in three regions (Fig. 2). When the grassland site was long enough, we worked along a 200-m transect with vegetation plots (4 m^2) every 50 m. At sites with different spatial formats, we sampled across four separate 50-m transects (not shown). The dark green quadrats denote areas where vegetation cover was assessed in detail; lighter green areas denote where a full plant species richness was collected as well as where butterflies and wild bees were sampled. Red dots show the locations of pooled soil samples taken for total carbon (SOC) and nitrogen, pH, soil texture, and microbial biomass (carbon based). Insects and flowering aspect were sampled four times over a growing season compared to vegetation once.

contextual and normative, collaboratively designed to identify and address potential sustainability challenges (Wanner et al. 2018)—an endeavor pursued in each of the study regions. Establishing RWLs across the study regions required addressing different contextual factors and social-ecological characteristics, highlighting the need to adapt approaches to the unique conditions and needs of each local context. Through inclusive communication and deliberation on perceptions, experiences, aspirations and expectations, a shared understanding of desirable futures was developed, and these in turn guided the goals of RWLs (sensu Leventon et al. 2016).

Each RWL aimed to address local issues related to grassland restoration, improve stakeholder engagement, promote sustainable practices and enhance the resilience of the social-ecological system associated with grasslands (for a detailed discussion of the role of social factors and stakeholder collaboration in enhancing restoration success, see Box 3). These objectives required a nuanced understanding of spatiotemporal variations in environmental and socioeconomic conditions, highlighting the need for adaptive restoration strategies (Table 3). For example, RWL North engaged regional stakeholders through a series of participatory workshops. This approach facilitated deliberative processes and social learning that allowed stakeholders to contribute to decision-making and co-create restoration strategies tailored to the specific needs of the region accounting for the diversity of values and worldviews on restoration. By fostering dialogue and collaboration, these workshops aimed to build trust, enhance local capacity and agency for sustainable practices, and ensure that restoration efforts were both contextually relevant and supported by all stakeholders. Meanwhile, the RWL Center emphasized the involvement of local stakeholders in restoration activities through citizen science programs and the monitoring of participatory pilot actions. This approach was designed to empower the community, improve scientific literacy and ensure ongoing stakeholder involvement in restoration efforts. In the RWL South, activities included the creation of an online forum for the community to share information about restoration projects. This digital platform aimed to facilitate knowledge sharing, promote community engagement and ensure transparency in restoration initiatives. Taken together, these different approaches reflect adaptive, context-specific strategies in RWLs, which are critical for helping to achieve long-term sustainability and resilience in grassland restoration efforts.

While short-term experiments within RWLs are valuable for immediate learning and adaptation, they often fail to capture the complexity and long-term perspective needed to understand and support sustainable transformations. Therefore, it is crucial to develop RWLs as research spaces with a broad spatial, temporal and thematic scope. This broader scope enables RWLs to address regional and local specificities while contributing to global knowledge, ensuring that interventions are contextually relevant and widely applicable.

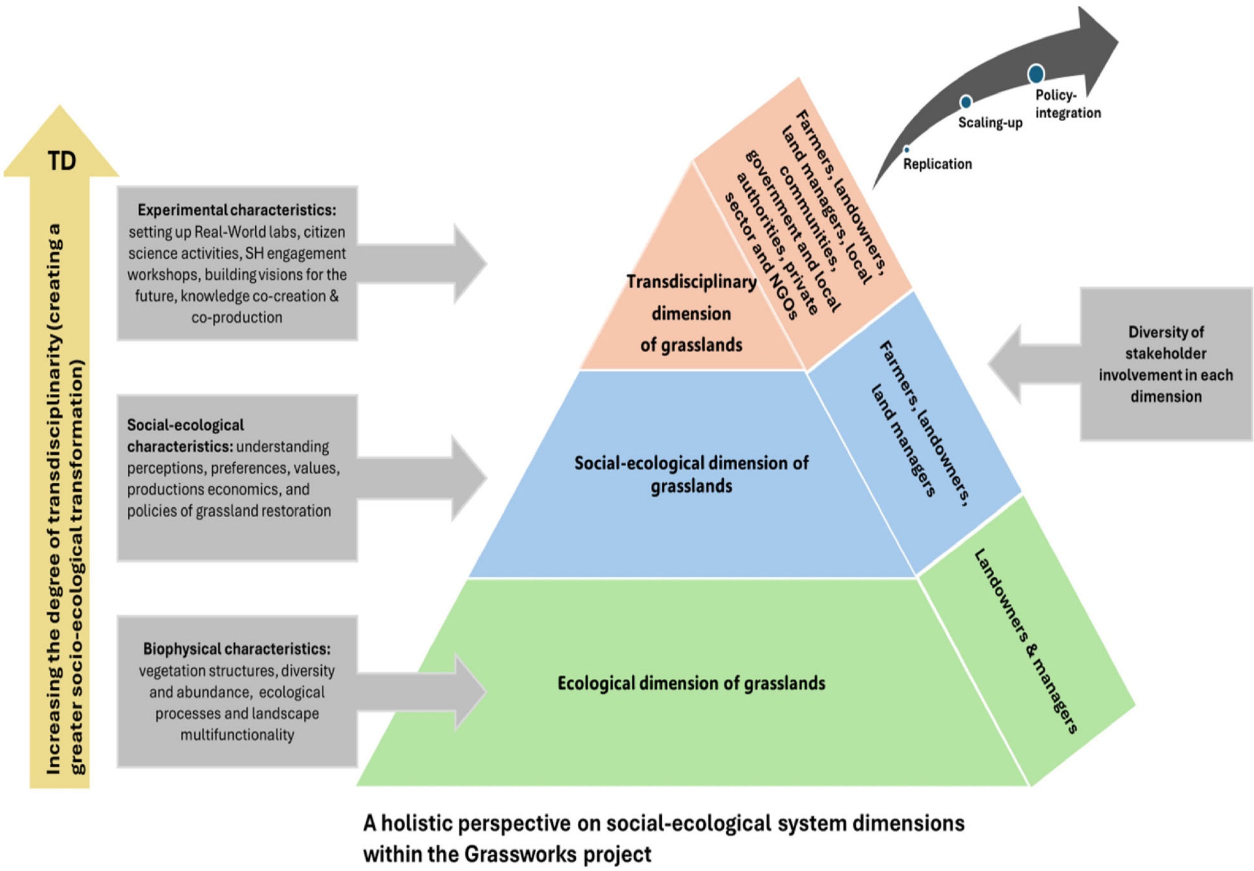
To operationalize and track advances and changes in the RWLs, we focused on three main components (see Table 3):

(1) Ex ante/ex post evaluation (for the Northern and Central Regions).
(2) Transdisciplinary knowledge co-creation during live restoration with local stakeholders.
(3) Demonstration sites.

As a first component, the ex ante evaluation measured stakeholders' initial views, including their values—such as the importance they place on grasslands for ecological, cultural or

Box 3 How social dimensions of restoration complement studying restoration success, by including social perspectives and social factors that influence processes and outcomes.

As one moves from ecological to social-ecological and finally to the transdisciplinary dimensions of grassland restoration, the diversity of stakeholders and the potential for social-ecological transformation increase. The transdisciplinary dimension integrates experimental approaches such as RWLs, citizen science activities, stakeholder workshops, and knowledge co-creation, fostering collaboration, trust and shared understanding among diverse stakeholders, including farmers, landowners, local communities, policymakers, and NGOs.



This integration of ecological, social-ecological, and transdisciplinary elements enhances the capacity for systemic and lasting change in grassland restoration. By addressing diverse values, practices, and knowledge systems, and through co-creation and shared decision-making, the process supports scaling up, identifying best practices, and embedding key findings into policy frameworks.

We view this gradient, culminating in transdisciplinary approaches, as a pathway toward stronger transformation with increased and more persistent restoration success. Such approaches are critical to addressing the current need for scaling up restoration efforts, as framed by the EU Restoration Law and the Kunming–Montreal Biodiversity Agreement.

Social-ecological approaches have clear advantages over the more traditional method of assessing restoration success based on ecological attributes of the ecosystem alone, in that factors that may be critical to the chances of a project being successful may lie as much in the realm of social components (framings, values held, priorities of stakeholders, capacity for monitoring before and after effects, power dynamics, network interactions) as in the level of ecological or biophysical drivers considered or ecological attributes measured.

Transdisciplinary social-ecological approaches take time however, as they, by definition, include more participants, who come from different backgrounds and may have different knowledge or value bases (Schäpke et al. 2024). There are indeed multiple levels of interdisciplinarity both within more natural science focused research projects but also within social-ecological research

Continued

Box 3 How social dimensions of restoration complement studying restoration success, by including social perspectives and social factors that influence processes and outcomes.—cont'd

framings as *Grassworks*, where not only the language used by scientists but the methods and approaches to extracting knowledge can differ ostensibly. Having a large number of social scientists working in the same project, often within the same work-packages, allows strong standardization potential but also potential for conflicting needs in relation to access to stakeholder for interviewing or surveying. This requires a high level of openness and exchange, as well as time.

economic reasons—and their knowledge, referring to their understanding of grassland biodiversity, ecosystem functions and restoration practices. It also assessed their motivations, visions and perceived barriers related to grasslands. The ex post evaluation, on the other hand, involved the assessment of changes in valuation of grasslands (and nature in general) and grassland restoration—also assessing the other aspects described above. The second component involved transdisciplinary co-creation with local stakeholders, focusing on identifying contextual issues related to live grassland restoration and co-creating knowledge using co-design methods. The third component was knowledge exchange using demonstration sites in all three regions to highlight multifunctional outcomes and share best practices.

Discussion

Synthesis and integration are critical in interdisciplinary projects like *Grasswork*s, where combining social, ecological and economic disciplines is essential for effectively addressing complex restoration challenges. By merging academic knowledge with practical expertise, we aimed to create a coherent interdisciplinary framework to inform both research and practice.

This effort was supported by our practice partner, Deutscher Verband für Landschaftspflege (DVL, Land Care Germany), who provided expert guidance and facilitated connections with stakeholders across Germany (see YouTube website with films developed by the DVL to inform practitioners on best practice methods: https://www.youtube.com/playlist?list=PLrA74x502hW7UKcXfjNat5zFbaSMOcqNn). As part of the synthesis, we developed a model of factors contributing to restoration success using Bayesian Belief Networks (BBNs; MacPherson et al. 2018). BBNs are acyclic graphs representing networks of variables and their dependencies. The structure of our BBN was co-designed through two workshops with the *Grassworks* consortium, integrating diverse perspectives with a strong focus on stakeholder views. While still under development, the final BBN will enable simulations and analyses to explore how changes in specific variables influence restoration success.

To support the application and transferability of our social-ecological framework, we propose a set of complementary approaches for assessing restoration success, tailored to the context, available data, and stakeholder perspectives. In our study, we did not adopt a uniform social-ecological system (Nagel & Partelow 2022) scoring matrix, as such systems can assume that outcomes are easily measurable in a numerical way, which is not easily the case when considering social aspects of success. In addition, such standardized scoring systems (including the Restoration Wheels proposed by Gann et al. 2019, in the Restoration Standards of the Society for Ecological Restoration) can be too rigid to capture the nuanced and context-dependent nature of restoration. Scoring frameworks often rely on fixed categories or numerical values that assume shared definitions of success, yet these interpretations can vary significantly across regions, cultures, and governance systems. This limits their utility for comparative or reflexive learning, especially when applied to complex and contested landscapes. Instead, we advocate for a flexible and adaptive assessment strategy. As mentioned before, we apply BBN analysis to integrate ecological, social, and economic data with expert knowledge, enabling us to model interactions between variables and explore different scenarios of restoration success. To complement this, we use a combined Analytic Hierarchy Process and Choice Experiment approach to investigate how different stakeholder groups prioritize restoration goals (Schmoldt et al. 2001). This approach reveals substantial variation in preferences, particularly between farming and non-farming actors, and highlights the need to account for multiple value systems in assessing multifunctionality. Using a social-ecological systems approach and engaging with the concept of "leverage points" (Abson et al. 2017), we also aim to identify key ecological, economic, and social factors that underpin restoration success. This perspective helps reveal which system elements and interactions have the greatest potential to trigger transformative change. Together, these frameworks offer a multidimensional and a more context-sensitive and iterative way of evaluating restoration processes and outcomes. Rather than promoting prescriptive measures, our aim is to support mutual learning, adaptive management, and constructive dialogue around what restoration success can and should mean in different contexts.

The integration of these approaches adds significant value by creating a framework that can be transferred and adapted across different spatial and social contexts. The replicability of the framework over time and space lies in its focus on key elements, including the consideration of spatial heterogeneity in grassland systems and the inclusion of diverse stakeholder perspectives across social scales. These attributes ensure the framework's applicability to different restoration projects and its potential to guide long-term, sustainable restoration efforts.

A key outcome of *Grassworks*, as part of our synthesis and integration efforts, will be an online restoration success estimation tool. Informed by ecological and social findings from *Grassworks*, including the BBN analysis, this tool will provide restoration practitioners with guidance and insights into the

Table 3. Key differences in characteristics and methodological approaches of real-world laboratories (RWLs) in the *Grassworks* project.

RWL Characteristics	*RWL North*	*RWL Center*	*RWL South*
Case study region	Landkreis Gifhorn, focus on Hankensbüttel and Drömling	Biosphere Reserve Karst Landscape Southern Harz, focus on Hainrode village	Donau-Isar lowland, Southern Bavaria, focus on Gauting Municipality
Cooperation partner	Gifhorn County, Aktion Fischotterschutz e., and Biohof Flegel KG	Heimat and Naturschutzverein Hainrode e. V.	
Economic characteristics of the region	Medium economic strength	Low economic strength	High economic strength
Biophysical characteristics of the region	Medium nutrient inputs and extensive grasslands owned by the cooperation partner are species-poor and degraded despite restoration efforts. Grasslands are scarce in the model region	Increasing risk of grassland fallow and loss of connectivity. However, target species and residual populations remain, indicating good regeneration potential with low nutrient inputs	Intensive agricultural use, high nutrient inputs, fertile soils. Grasslands threatened by plowing, gravel extraction, and dyke construction
Demonstration site(s)	Long-term grassland experiment testing potential of priority effects (POEM project, Alonso-Crespo et al. 2025) for multifunctional outcomes	Long-term species-rich grassland fertilization experiments in Hayn (Saxony-Anhalt; Dullau et al. 2023) aiming at high plant biodiversity and productivity outcomes	Long-term dike restoration experiment (Bauer et al. 2024) testing site characteristics, spatial and historical effects on restoration outcomes near the Danube (Lower Bavaria)
Live Restoration	(a) Rewetting of grasslands and testing potential for using biodiversity and priority effects for multifunctional outcomes (Hankensbüttel) (b) Restoration intervention with hay transfer from donor to receiver sites part of compensation for building (Drömling)	Establishment of five species-rich grassland areas in Hainrode, accompanied by informational and educational materials (e.g., informational signs, a citizen science brochure, distribution of seed packets, and an information booth at village events)	Improvement of a municipal grassland site through a simple experiment: sowing regional seed at two densities and with four soil preparation methods (topsoil removal, grubbing, rotary tilling, management adaption/no preparation); Includes a student project and resident's engagement through an online forum, informational signs, and a live event (Feldtag)
Approaches and methods used in the RWL	Transdisciplinary process for the co-creation and implementation of a long-term pilot restoration concept in collaboration with local stakeholders. Value-based envisioning workshop, restoration concept world-café workshop, ex ante/ex post comparison, qualitative interviews, group deliberative Q-method, and social network analysis	Participatory mapping exercise for the site selection process (workshop), vegetation surveys, photovoice, focus groups, citizen science activities, and ex ante/ex post surveys	Vegetation surveys before/after sowing, photo documentation; discussions through online forum, ex ante/(ex post is pending); field day

likelihood of success. Furthermore, all ecological data generated during the project will be uploaded with the help of GFBio (German Federation of Biological Data) to the public repository PANGAEA (Felden et al. 2023) in accordance with FAIR principles (Wilkinson et al. 2016) and will be made publicly available following a 2-year moratorium.

With the EU Nature Restoration Law, along with EU and national biodiversity strategies now firmly on the political agenda, the need to scale up ecological restoration is greater than ever. Upscaling is not only a question of increasing the area that is restored, but also a social-ecological endeavor that requires strong links and communication between science and practice as well as across different social spheres of society. The *Grassworks* project has made significant progress in this regard by fostering collaboration between researchers and practitioners, integrating ecological, social, and economic dimensions, to inform and guide scalable and transferable restoration efforts. However, as with many transdisciplinary projects, *Grassworks* faced limitations, including challenges of stakeholder engagement and availability, variability of physical factors such as climate change, and administrative barriers as part of bureaucratic processes. In addition, the complexity of aligning diverse stakeholder interests and integrating knowledge across disciplines required considerable effort and coordination. Effective stakeholder engagement in restoration requires more than broad participation, it demands critical reflection on how power is distributed among actors. Unequal power dynamics can seriously hinder restoration outcomes, particularly when interventions disrupt established land-use legacies or dominant socioeconomic interests. Evidence from various regions shows that when stakeholders feel excluded or perceive restoration efforts as externally imposed, they may not only disengage but also actively resist or obstruct implementation (Mikulcak et al. 2015). Such resistance can manifest through power imbalances, noncompliance, or the erosion of local stewardship structures. Conflicts frequently emerge from competing land use priorities, competition over limited resources and their allocation, and asymmetries in access to information and decision-making influence. These tensions are often exacerbated by unresolved historical legacies, deeply rooted cultural norms, and institutional ambiguity regarding legal roles and responsibilities (Mansourian et al. 2025). Where governance systems lack transparency and accountability, trust deteriorates, and the possibility of a shared restoration vision becomes increasingly remote. In response, our framework emphasizes the need for adaptive, context-sensitive strategies that address the complex realities of stakeholder engagement in restoration. A key challenge lies in reconciling global or national restoration goals with the diversity and reality of local contexts, interests, and governance arrangements. Achieving this requires processes that foster inclusive dialogue, mitigate power imbalances, and support collaborative decision-making (Colloff et al. 2025). Equally important is the creation of flexible spaces where disagreement can be expressed and negotiated constructively. Rather than reinforcing polarized debates, such approaches should allow for the exploration of diverse perspectives, which can lead to more legitimate, resilient, and equitable restoration outcomes (Loos et al. 2024).

To overcome stakeholder resistance and policy inertia, we propose integrating approaches to "future-thinking," "backcasting," and "participatory scenario narratives" as strategic tools for envisioning desirable futures and charting pathways to achieve them (Manning et al. 2006; Dorninger et al. 2020; Cork et al. 2023). These tools can help people from diverse backgrounds reach a common understanding of important issues, identify underlying causes, and pathways toward optimistic futures. The roles of exploring alternative futures in breaking unhelpful social and political blockages and in conflict resolution are key emerging topics. Analyzing policy contexts and identifying regulatory bottlenecks also play an important role in mitigating inertia and aligning ecological objectives with stakeholder values. These limitations highlight the continuing need for adaptive approaches and flexible frameworks to address the specific challenges of transdisciplinary and collaborative research projects.

In parallel, we highlight the importance of embedding conflict resolution mechanisms—such as joint problem-solving and mutual understanding—within stakeholder engagement processes to foster trust and legitimacy (Moore et al. 2023). Our framework stresses that participatory processes, particularly in RWL settings, create opportunities for shared ownership and co-creation, which are essential for overcoming resistance. Adaptive governance models, characterized by iterative learning, local experimentation, and institutional flexibility, offer a robust pathway for managing contested restoration efforts (Chaffin & Gunderson 2016; Bodin 2017). Polycentric governance arrangements further support this process by operating across multiple levels and sectors, enabling more inclusive and context-responsive decision-making (Terrisse et al. 2025). These governance models require durable participatory structures and trust-based relationships, which can catalyze collective action (Folke et al. 2005). Acknowledging the social and political dimensions of restoration, therefore, is not simply a technical requirement but a transformative imperative for enabling more effective and equitable restoration outcomes (Loos et al. 2022).

For restoration to be as successful as possible, attention must broaden the conventional and project-based lens of ecological objectives to situating restoration as a process within a social-ecological system, integrating different values, practices, knowledge and goals, across different stakeholder groups (Cortés-Capano et al. 2022, 2025). While we already have substantial knowledge on the factors contributing to ecological success in grassland restoration, it is important to acknowledge that restoration efforts can face challenges and sometimes fail to fully achieve their goals. *Grassworks* builds on this knowledge foundation by employing standardized sampling across three regions and, for the first time, assessing the critical role of social as well as the holistic social-ecological components that drive restoration success. We consider that the outcomes from the social-ecological *Grassworks* project, being synthetic and integrative across a range of different grassland vegetation types as well as including a broader epistemological lens, will provide a strong evidence base for informing on the ground grassland restoration in Germany, but also in many other countries in Europe within the framing of the EU Restoration Law. Since the dynamics of grasslands across central and northern Europe are generally influenced by similar drivers of degradation (intensification of land use, eutrophication, bush encroachment, etc.) and the need for social-ecological whole system approaches to restoration are on the rise, we anticipate that our findings and this methods paper should provide some key insights for upcoming projects and restoration activities.

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LITERATURE CITED

Abson DJ, Fischer J, Leventon J, Newig J, Schomerus T, Vilsmaier U, et al. (2017) Leverage points for sustainability transformation. Ambio 46:30–39. https://doi.org/10.1007/S13280-016-0800-Y

Alonso-Crespo IM, Temperton VM, Fichtner A, Niemeyer T, Schloter M, Delory BM (2025) Exploring Priority and Year Effects on Plant Diversity, Productivity and Vertical Root Distribution: First Insights From a Grassland Field Experiment. Journal Vegetation Science I36:e70026. https://doi.org/10.1111/jvs.70026

Asma Ben-Othmen M, Ostapchuk M, Ben-Othmen MA (2023) How diverse are farmers' preferences for large-scale grassland ecological restoration? Evidence from a discrete choice experiment. Review of Agricultural, Food and Environmental Studies 104:341–375. https://doi.org/10.1007/s41130-023-00200-x

Bardgett RD, Bullock JM, Lavorel S, Manning P, Schaffner U, Ostle N, et al. (2021) Combatting global grassland degradation. Nature Reviews Earth & Environment 2:720–735. https://doi.org/10.1038/s43017-021-00207-2

Bauer, M., Huber, JK., Kollmann, J. (2024). Beta diversity of restored river dike grasslands is strongly influenced by uncontrolled spatio-temporal variability. Journal of Vegetation Science, 35, e13293. Available from: https://doi.org/10.1111/jvs.13293

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

Bergmann M, Schäpke N, Marg O, Stelzer F, Lang DJ, Bossert M, et al. (2021) Transdisciplinary sustainability research in real-world labs: success factors and methods for change. Sustainability Science 16:541–564. https://doi.org/10.1007/S11625-020-00886-8

Blickensdörfer L, Schwieder M, Pflugmacher D, Nendel C, Erasmi S, Hostert P (2022) Mapping of crop types and crop sequences with combined time series of Sentinel-1, Sentinel-2 and Landsat 8 data for Germany. Remote Sensing of Environment 269:112831. https://doi.org/10.1016/j.rse.2021.112831

Bodin Ö (2017) Collaborative environmental governance: achieving collective action in social-ecological systems. Science 357:eaan1114. https://doi.org/10.1126/Science.aan1114

Broeckhoven N, Cliquet A (2015) Gender and ecological restoration: time to connect the dots. Restoration Ecology 23:729–736. https://doi.org/10.1111/rec.12270

Brudvig LA (2017) Toward prediction in the restoration of biodiversity. Journal of Applied Ecology 54:1013–1017. https://doi.org/10.1111/1365-2664.12940

Bucharova A, Krahulec F (2020) Native seed addition as an effective tool for post-invasion restoration. Basic and Applied Ecology 42:54–61. https://doi.org/10.1016/j.baae.2020.01.002

Buckingham K, Arakwiye B, Ray S, Maneerattana O, Anderson W (2021) Cultivating networks and mapping social landscapes: how to understand restoration governance in Rwanda. Land Use Policy 104:104546. https://doi.org/10.1016/j.landusepol.2020.104546

Bundesamt für Kartographie und Geodäsie (2023) Digitale orthophotos bodenauflösung 20 cm. https://gdz.bkg.bund.de/index.php/default/digitale-orthophotos-bodenauflosung-20-cm-dop20.html (accessed 1 June 2025)

Canessa C, Venus TE, Wiesmeier M, Mennig P, Sauer J (2023) Incentives, rewards or both in payments for ecosystem services: drawing a link between farmers' preferences and biodiversity levels. Ecological Economics 213:107954. https://doi.org/10.1016/j.ecolecon.2023.107954

Carlucci MB, Brancalion PHS, Rodrigues RR, Loyola R, Cianciaruso MV (2020) Functional traits and ecosystem services in ecological restoration. Restoration Ecology 28:1372–1383. https://doi.org/10.1111/rec.13279

Chaffin BC, Gunderson LH (2016) Emergence, institutionalization and renewal: rhythms of adaptive governance in complex social-ecological systems. Journal of Environmental Management 165:81–87. https://doi.org/10.1016/j.jenvman.2015.09.003

Choi YD, Temperton VM, Allen EB, Grootjans AP, Halassy M, Hobbs RJ, Naeth MA, Torok K (2008) Ecological restoration for future sustainability in a changing environment. Ecoscience 15:53–64. https://doi.org/10.2980/1195-6860(2008)15[53:erffsi]2.0.CO;2

Chytrý M, Tichý L, Hennekens SM, Knollová I, Janssen JAM, Rodwell JS, et al. (2020) EUNIS habitat classification: expert system, characteristic species combinations and distribution maps of European habitats. Applied Vegetation Science 23:648–675. https://doi.org/10.1111/avsc.12519

Colloff MJ, Gorddard R, Munera-Roldán C, Locatelli B, Lavorel S, Allain S, et al. (2025) Changing the decision context to enable social learning for climate adaptation. People and Nature 00:20. https://doi.org/10.1002/pan3.70043

Cork S, Alexandra C, Alvarez-Romero JG, Bennett EM, Berbés-Blázquez M, Bohensky E, et al. (2023) Exploring alternative futures in the Anthropocene. Annual Review of Environment and Resources 48:25–54. https://doi.org/10.1146/annurev-environ-112321-095011

Cortés-Capano G, Hausmann A, Di Minin E, Kortetmäki T (2022) Ethics in biodiversity conservation: the meaning and importance of pluralism. Biological Conservation 275:109759. https://doi.org/10.1016/j.biocon.2022.109759

Cortés-Capano G, Loos J, Hausmann A, Kortetmäki T (2025) Sensemaking and abductive reasoning for transformative biodiversity conservation. People and Nature 7:1–13. https://doi.org/10.1002/pan3.70055

De Groot RS, Blignaut J, Van Der Ploeg S, Aronson J, Elmqvist T, Farley J (2013) Benefits of investing in ecosystem restoration. Conservation Biology 27:1286–1293. https://doi.org/10.1111/cobi.12158

Dengler J, Janišová M, Török P, Wellstein C (2014) Biodiversity of Palaearctic grasslands: a synthesis. Agriculture, Ecosystems & Environment 182:1–14. https://doi.org/10.1016/j.agee.2013.12.015

Dorninger C, Abson DJ, Apetrei CI, Derwort P, Ives CD, Klaniecki K, et al. (2020) Leverage points for sustainability transformation: a review on interventions in food and energy systems. Ecological Economics 171:106570. https://doi.org/10.1016/j.ecolecon.2019.106570

Dullau S, Kirmer A, Tischew S, Holz F, Meyer MH, Schmidt A (2023) Effects of fertilizer levels and drought conditions on species assembly and biomass

production in the restoration of a mesic temperate grassland on ex-arable land. Global Ecology and Conservation 48:e02730. https://doi.org/10.1016/j.gecco.2023.e02730
Elias M, Joshi D, Meinzen-Dick R (2021) Restoration for whom, by whom? A feminist political ecology of restoration. Ecological Restoration 39:3–15. https://doi.org/10.3368/er.39.1-2.3
Felden J, Möller L, Schindler U, Huber R, Schumacher S, Koppe R, et al. (2023) PANGAEA—data publisher for Earth & Environmental Science. Scientific Data 10:1–9. https://doi.org/10.1038/S41597-023-02269-X
Fernández-Manjarrés JF, Roturier S, Bilhaut AG (2018) The emergence of the social-ecological restoration concept. Restoration Ecology 26:404–410. https://doi.org/10.1111/rec.12685
Fischer J, Riechers M, Loos J, Martin-Lopez B, Temperton VM (2021) Making the UN decade on ecosystem restoration a social-ecological endeavour. Trends in Ecology & Evolution 36:20–28. https://doi.org/10.1016/j.tree.2020.08.018
Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30:441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511
Funk JL, Eviner VT, Garbowski M, Valliere JM (2024) Empirical tests of trait–function relationships are crucial for advancing trait-based restoration: a response to merchant et al. (2023). Restoration Ecology 32:e14254. https://doi.org/10.1111/rec.14254
Funk JL, Larson JE, Ames GM, Butterfield BJ, Cavender-Bares J, Firn J, Laughlin DC, Sutton-Grier AE, Williams L, Wright J (2017) Revisiting the holy grail: using plant functional traits to understand ecological processes. Biological Reviews 92:1156–1173. https://doi.org/10.1111/brv.12275
Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, et al. (2019) International principles and standards for the practice of ecological restoration. Restoration Ecology 27:S1–S46. https://doi.org/10.1111/rec.13035
Hellwig N, Schubert LF, Kirmer A, Tischew S, Dieker P (2022) Effects of wildflower strips, landscape structure and agricultural practices on wild bee assemblages—a matter of data resolution and spatial scale? Agriculture, Ecosystems & Environment 326:107764. https://doi.org/10.1016/j.agee.2021.107764
Helm A, Zobel M, Moles AT, Szava-Kovats R, Pärtel M (2015) Characteristic and derived diversity: implementing the species pool concept to quantify conservation condition of habitats. Diversity and Distributions 21:711–721. https://doi.org/10.1111/ddi.12285
Hess MCM, Buisson E, Fontes H, Bacon L, Sabatier F, Mesléard F (2020) Giving recipient communities a greater head start and including productive species boosts early resistance to invasion. Applied Vegetation Science 23:340–352. https://doi.org/10.1111/avsc.12502
Hijmans RJ, Barbosa M, Ghosh A, Mandel A (2024) Geodata: download geographic data. In: CRAN: contributed packages. The R Foundation for Statistical Computing, Vienna, Austria. https://doi.org/10.32614/cran.package.geodata
Huber R, Finger R (2020) A meta-analysis of the willingness to pay for cultural services from grasslands in Europe. Journal of Agricultural Economics 71:357–383. https://doi.org/10.1111/1477-9552.12361
Jandt U, Bruelheide H, Jansen F, Bonn A, Grescho V, Klenke RA, et al. (2022) More losses than gains during one century of plant biodiversity change in Germany. Nature 611:512–518. https://doi.org/10.1038/s41586-022-05320-w
Kirmer A, Tischew S, Ozinga WA, Von Lampe M, Baasch A, Van Groenendael JM (2008) Importance of regional species pools and functional traits in colonization processes: predicting re-colonization after large-scale destruction of ecosystems. Journal of Applied Ecology 45:1523–1530. https://doi.org/10.1111/j.1365-2664.2008.01529.x
Knight ML, Overbeck GE (2021) How much does is cost to restore a grassland? Restoration Ecology 29:e13463. https://doi.org/10.1111/rec.13463
Landesvermessungsamt Sachsen-Anhalt (LVermGeo) (n.d.) Geodaten & Karten. https://www.lvermgeo.sachsen-anhalt.de/de/gdp-geodaten-karten.html
Leventon J, Fleskens L, Claringbould H, Schwilch G, Hessel R (2016) An applied methodology for stakeholder identification in transdisciplinary research. Sustainability Science 11:763–775. https://doi.org/10.1007/s11625-016-0385-1
Loos J, Benra F, Berbés-Blázquez M, Bremer LL, Chan KMA, Egoh B, et al. (2022) An environmental justice perspective on ecosystem services. Ambio 52:477–488. https://doi.org/10.1007/S13280-022-01812-1
Loos J, Cortés-Capano G, Riechers M, Walsh C, Leventon J (2024) Enhancing the transformative potential of interventions for the sustainable use of natural resources. Biological Conservation 296:110691. https://doi.org/10.1016/j.biocon.2024.110691
Lyons KG, Török P, Hermann JM, Kiehl K, Kirmer A, Kollmann J, et al. (2023) Challenges and opportunities for grassland restoration: a global perspective of best practices in the era of climate change. Global Ecology and Conservation 46:e02612. https://doi.org/10.1016/j.gecco.2023.e02612
MacPherson MP, Webb EB, Raedeke A, Mengel D, Nelson F (2018) A review of Bayesian belief network models as decision-support tools for wetland conservation: Are water birds potential umbrella taxa? Biological Conservation 226:215–223. https://doi.org/10.1016/j.biocon.2018.08.001
Manning AD, Lindenmayer DB, Fischer J (2006) Stretch goals and backcasting: approaches for overcoming barriers to large-scale ecological restoration. Restoration Ecology 14:487–492. https://doi.org/10.1111/j.1526-100x.2006.00159.x
Mansourian S, Djenontin INS, Elias M, Oldekop JA, Derkyi MAA, Kull CA, Pacheco P (2025) Ecosystem restoration centered in people. Restoration Ecology 33:e70049. https://doi.org/10.1111/rec.70049
Martin DM (2017) Ecological restoration should be redefined for the twenty-first century. Restoration Ecology 25:668–673. https://doi.org/10.1111/rec.12554
Messier C, Puettmann K, Chazdon R, Andersson KP, Angers VA, Brotons L, Filotas E, Tittler R, Parrott L, Levin SA (2015) From management to stewardship: viewing forests As complex adaptive Systems in an Uncertain World. Conservation Letters 8:368–377. https://doi.org/10.1111/conl.12156
Mikulcak F, Haider JL, Abson DJ, Newig J, Fischer J (2015) Applying a capitals approach to understand rural development traps: a case study from post-socialist Romania. Land Use Policy 43:248–258. https://doi.org/10.1016/j.landusepol.2014.10.024
Montoya D, Rogers L, Memmott J (2012) Emerging perspectives in the restoration of biodiversity-based ecosystem services. Trends in Ecology & Evolution 27:666–672. https://doi.org/10.1016/j.tree.2012.07.004
Moore ML, Hermanus L, Drimie S, Rose L, Mbaligontsi M, Musarurwa H, et al. (2023) Disrupting the opportunity narrative: navigating transformation in times of uncertainty and crisis. Sustainability Science 18:1649–1665. https://doi.org/10.1007/s11625-023-01340-1
Nagel B, Partelow S (2022) A methodological guide for applying the social-ecological system (SES) framework: a review of quantitative approaches. Ecology and Society 27:39. https://doi.org/10.5751/es-13493-270439
Nerlekar AN, Sullivan LL, Brudvig LA (2024) Grassland restorations must better foster forbs to facilitate high biodiversity. Restoration Ecology 32:e14214. https://doi.org/10.1111/rec.14214
Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN) (2023) Vollzugshinweise für Arten und Lebensraumtypen. https://www.nlwkn.niedersachsen.de/vollzugshinweise-arten-lebensraumtypen/vollzugshinweise-fuer-arten-und-lebensraumtypen-46103.html
Padgham M, Lovelace R, Salmon M, Rudis B (2017) Osmdata. The Journal of Open Source Software 2:305. https://doi.org/10.21105/joss.00305
Pebesma E, Bivand R (2023) Spatial data science: with applications in R. Chapman and Hall/CRC, New York. https://doi.org/10.1201/9780429459016
Perring MP, Erickson TE, Brancalion PHS (2018) Rocketing restoration: enabling the upscaling of ecological restoration in the Anthropocene. Restoration Ecology 26:1017–1023. https://doi.org/10.1111/rec.12871
Pfadenhauer J (2001) Some remarks on the socio-cultural background of restoration ecology. Restoration Ecology 9:220–229. https://doi.org/10.1046/j.1526-100x.2001.009002220.x

Poeplau C, Don A, Flessa H, Heidkamp A, Jacobs A, Prietz R (2020) Erste Bodenzustandserhebung Landwirtschaft – Kerndatensatz. https://doi.org/10.3220/data20200203151139

Pollard E (1977) A method for assessing changes in the abundance of butterflies. Biological Conservation 12:115–134. https://doi.org/10.1016/0006-3207(77)90065-9

Reed MS, Merkle BG, Cook EJ, Hafferty C, Hejnowicz AP, Holliman R, et al. (2024) Reimagining the language of engagement in a post-stakeholder world. Sustainability Science 19:1481–1490. https://doi.org/10.1007/s11625-024-01496-4

Schäpke N, Beecroft R, Wanner M, Wagner F, Rhodius R, Laborgne P, Parodi O (2024) Gaining deep leverage? Reflecting and shaping real-world lab impacts through leverage points. GAIA – Ecological Perspectives for Science and Society 33:116–124. https://doi.org/10.14512/gaia.33.S1.17

Schäpke N, Stelzer F, Caniglia G, Bergmann M, Wanner M, Singer-Brodowski M, Loorbach D, Olsson P, Baedeker C, Lang DJ (2018) Jointly experimenting for transformation? Shaping real-world laboratories by comparing them. GAIA – Ecological Perspectives for Science and Society 27: 85–96. https://doi.org/10.14512/gaia.27.S1.16

Schmoldt DL, Kangas J, Mendoza GA, Pesonen M (2001) The analytic hierarchy process in natural resource and environmental decision making. Vol 3. Springer, Dordrecht. https://doi.org/10.1007/978-94-015-9799-9

Schwieder M, Wesemeyer M, Frantz D, Pfoch K, Erasmi S, Pickert J, Nendel C, Hostert P (2022) Mapping grassland mowing events across Germany based on combined Sentinel-2 and Landsat 8 time series. Remote Sensing of Environment 269:112795. https://doi.org/10.1016/j.rse.2021.112795

Shackelford N, Dudney J, Stueber MM, Temperton VM, Suding KL (2021*a*) Measuring at all scales: sourcing data for more flexible restoration references. Restoration Ecology 32:e13541. https://doi.org/10.1111/rec.13541

Shackelford N, Hobbs RJ, Burgar JM, Erickson TE, Fontaine JB, Laliberté E, Ramalho CE, Perring MP, Standish RJ (2013) Primed for change: developing ecological restoration for the 21st century. Restoration Ecology 21: 297–304. https://doi.org/10.1111/rec.12012

Shackelford N, Paterno GB, Winkler DE, Erickson TE, Leger EA, Svejcar LN, et al. (2021*b*) Drivers of seedling establishment success in dryland restoration efforts. Nature Ecology & Evolution 5:1283–1290. https://doi.org/10.1038/S41559-021-01510-3

Shipley JR, Frei ER, Bergamini A, Boch S, Schulz T, Ginzler C, et al. (2024) Agricultural practices and biodiversity: conservation policies for semi-natural grasslands in Europe. Current Biology 34:R753–R761. https://doi.org/10.1016/j.cub.2024.06.062

Socher SA, Prati D, Boch S, Müller J, Baumbach H, Gockel S, et al. (2013) Interacting effects of fertilization, mowing and grazing on plant species diversity of 1500 grasslands in Germany differ between regions. Basic and Applied Ecology 14:126–136. https://doi.org/10.1016/j.baae.2012.12.003

Squires VR, Jürgen D (2018) Grasslands of the world. CRC Press, Boca Raton. https://doi.org/10.1201/9781315156125

Staude IR, Segar J, Temperton VM, Andrade BO, de Sá Dechoum M, Weidlich EWA, Overbeck GE (2023) Prioritize grassland restoration to bend the curve of biodiversity loss. Restoration Ecology 31:e13931. https://doi.org/10.1111/rec.13931

Tedesco AM, López-Cubillos S, Chazdon R, Rhodes JR, Archibald CL, Pérez-Hämmerle KV, et al. (2023) Beyond ecology: ecosystem restoration as a process for social-ecological transformation. Trends in Ecology & Evolution 38:643–653. https://doi.org/10.1016/j.tree.2023.02.007

Terrisse A, Karner M, Kaufmann J, Ernoul L (2025) Characterizing governance models for upscaling wetland restoration. Environmental Management 75:1155–1167. https://doi.org/10.1007/s00267-025-02132-2

Tivian (2024) Unipark survey software [Online survey platform]. https://www.unipark.com/

Traveset A, Heleno R, Chamorro S, Vargas P, Mcmullen CK, Castro-Urgal R, Nogales M, Herrera HW, Olesen JM (2013) Invaders of pollination networks in the Galápagos Islands: emergence of novel communities. Proceedings of the Royal Society B: Biological Sciences 280:20123040. https://doi.org/10.1098/rspb.2012.3040

von Drachenfels O (2021) Kartierschlüssel für Biotoptypen in Niedersachsen unter besonderer Berücksichtigung der gesetzlich geschützten Biotope sowie der Lebensraumtypen von Anhang I der FFH-Richtlinie, Stand März 2021. Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, Hannover

Waldén E, Lindborg R (2018) Facing the future for grassland restoration – what about the farmers? Journal of Environmental Management 227:305–312. https://doi.org/10.1016/j.jenvman.2018.08.090

Wanner M, Hilger A, Westerkowski J, Rose M, Stelzer F, Schäpke N (2018) Towards a cyclical concept of real-world laboratories: a transdisciplinary research practice for sustainability transitions. disP – The Planning Review 54:94–114. https://doi.org/10.1080/02513625.2018.1487651

Wesche K, Krause B, Culmsee H, Leuschner C (2012) Fifty years of change in Central European grassland vegetation: large losses in species richness and animal-pollinated plants. Biological Conservation 150:76–85. https://doi.org/10.1016/j.biocon.2012.02.015

Wickham H, Averick M, Bryan J, Chang W, McGowan L, François R, et al. (2019) Welcome to the tidyverse. Journal of Open Source Software 4: 1686. https://doi.org/10.21105/joss.01686

Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, et al. (2016) Comment: the FAIR guiding principles for scientific data management and stewardship. Scientific Data 3:1–9. https://doi.org/10.1038/sdata.2016.18

Wortley L, Hero JM, Howes M (2013) Evaluating ecological restoration success: a review of the literature. Restoration Ecology 21:537–543. https://doi.org/10.1111/rec.12028

Zedler JB (2007) Success: an unclear, subjective descriptor of restoration outcomes. Ecological Restoration 25:162–168. https://doi.org/10.3368/er.25.3.162

Zerbe S (2023) Pages 487–505. Restoration economy: costs and benefits. Springer Spektrum, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-65658-7_23

Supporting Information

The following information may be found in the online version of this article:

Table S1. Braun–Blanquet plant cover scale.
Table S2. Overview of questions asked to stakeholders in preparation for identifying key factors affecting restoration success outcomes as well as key components of restoration projects.
Table S3. Overview of data sources for retrieving remote sensing data on surrounding landscape around restored grassland sites.

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