Proposing a socialecological framework for successful grassland restoration in Germany – an overview and insights from the *Grassworks* project

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Abstract

Bending the biodiversity curve and delivering on biodiversity promises from international agreements and laws, including Kunming-Montreal and the EU Restoration Law, requires upscaling ecological restoration from smaller to larger spatial and temporal dimensions and across different spheres of society. Achieving this depends on a strong scientific evidence base and synthesis of effective practices from both ecological and social perspectives.

The *Grassworks* project investigates the factors driving success in grassland restoration in Germany, addressing ecological, socio-economic, and socialecological dimensions. We address this by conducting a post-hoc assessment of previously restored sites, comparing them to both positive and negative reference sites across three regions along a north-south gradient in Germany. In the post-hoc assessment, we employed a stratified design to evaluate the effects of restoration methods, previous land use, current management, governance, finance, and time since restoration intervention. We assessed vegetation, butterflies, wild bees, soil characteristics, and economic performance, while controlling for surrounding landscape configuration. Additionally, we examined key socialecological dimensions, including stakeholder values, knowledge exchange, and decision-making processes within established networks. This was complemented by a Real-World Laboratory approach, integrating ex-ante and ex-post assessments, demonstration sites, and live restoration activities co-created with local stakeholders.

This publication provides an overview and reflection, drawing on insights from the *Grassworks* project in Germany, to inform, guide and support the development of future large-scale socialecological restoration efforts worldwide.

Keywords: governance, grassland, multifunctionality, open ecosystems, production economics, restoration success, socialecological approach, stakeholder engagement, transdisciplinarity

Implications for Practice

- Legal framings such as the EU Restoration Law or the Kunming-Montreal Biodiversity Agreement now require a strong evidence base for scaling up restoration initiatives on the ground. Applying a socialecological lens to what constitutes success in restoration as well as integrating findings across regions promise to contribute significantly to providing such a science and practice driven evidence base. The socialecological 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 requires frequent communication and a common language as well as trust between scientists from disparate fields of enquiry (across natural and social sciences). This required a high level of openness and as well as time. The level of communication and amount of time required is rewarded with more generalisable, broad, robust and integrative outcomes, however.

Introduction: setting the scene

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. 2022), and covering more than a third of terrestrial land globally (Squires et al. 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 (Tischew et al 2008; Helm et al. 2015; Hess et al. 2020; Shackelford et al. 2021a) or more recently improving biotic interactions such as plant–pollinator networks (Montoya et al. 2012; Traveset et al. 2023). Socio-political, cultural or economic factors have so far received limited attention in the assessment of restoration success (but see 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 of evaluation of restoration success and economic incentives (Huber & Finger 2020), integrative approaches that combine economic with ecological and socialecological factors remain rare. Examples of social framings influencing restoration success, include ecologically valuable wildflower meadows being threatened with destruction in urban areas where the city authorities consider selling the land for building (personal communication), or tree planting initiatives being ecologically sound but failing due to the planting activities occurring at the wrong time of the year (Messier et al. 2014). At the same time, these projects or initiatives significantly affect the lives of individuals, 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 socio-economic 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; Fischer et al. 2021; Buckingham 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, 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 this inter- and transdisciplinary project, *Grassworks*, we aim to holistically fill this research gap by investigating under what conditions grassland restoration is successful, explicitly including ecological, socialecological as well as socio-economic 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 favourable condition, and 75% showing negative trends (Wesche et al. 2012; see also Dengler & Tischew 2018). 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 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. 2020).

In the *Grassworks* Project, we address the central research question: 'What leads to success in grassland restoration in Germany?' by exploring ecological, socio-economic, and socialecological dimensions. We propose a synthetic integration (*sensu* Fischer et al. 2021) 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 socialecological restoration efforts (https://grassworksprojekt.de/en/). The project integration focuses on three regions in Germany, thus 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 (Stocher 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: firstly, **it provides an overview of the approach and methods used to assess ecological, socialecological and socio-economic restoration success** across three different regions in Germany (North, Centre, 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 socialecological transformations (see 'leverage points' in Abson et al. 2017) and guide future cost-effective strategies to maximize the likelihood of restoration success.

Design of the *Grassworks* project

From a socialecological perspective, the most successful grassland restoration can be defined as a process that considers the ecological components, social aspects and socio-economic 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 diversity 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 et al. 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 socialecological 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 the society, but it is inevitably connected with costs for initial restoration and maintenance which are often borne by farmers and landowners (Zerbe 2023). From a socio-economic perspective, restoration success translates at the societal level into positive social net-benefits or high benefit-cost ratios, indicators which require that all costs and benefits to all members of the society are 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 perspective are typical indicators of successful restoration (Waldén & Lindbog 2018, Ben-Othmen & Ostapchuk 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 socialecological 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 hypothesise that the higher the ecological complexity and social engagement are, the higher the restoration success will be (Figure 1). To maximise the potential for restoration success, *Grassworks* is creating an integrative framework that can be used to identify potential scenarios for how ecosystem multifunctionality can be enhanced through the process of grassland restoration.

Main Rationale of the Study Design: three regions as a natural landscape experiment and a real-world lab for transformation and learning

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 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 (Peisker 2023; https://de.statista.com/statistik/daten/studie/73061/umfrage/bundeslaender-im-vergleich-bruttoinlandsprodukt/). For both the Centre (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 set up

We developed a post-hoc assessment to provide a holistic analysis of factors that affect grassland restoration success in Germany, collecting ecological, socialecological and economic data in grasslands already restored by local stakeholders in the three regions (Figure 2). Data was 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, giving a total of 187 sites (with around 40 restored sites plus ten positive and ten negative sites per region; Table 2). We included dry, fresh and moist to wet grassland types (excluding only grasslands on peat soils). Target vegetation types measured (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 socialecological characteristics. Our design was chosen 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 Box 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 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, i.e. 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 (Figure 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 x 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 (Figure 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 on the whole 1000 m^2-transect. The maximum duration allocated for sampling additional plant species was one hour. 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 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 analysed for total soil organic carbon (SOC), total nitrogen content, 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. The soil and bulk density samples were taken at two depths, namely 0–10 and 10–30 cm since these depths are commonly sampled across Germany and allow for national and international comparison.

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 Figure 3). Butterflies were counted using the Pollard walk method (Pollard 1977), and wild bees were collected by sweep netting for 5 min within each 50-m sub-transect section, resulting in a total of 20 min of observation per transect. Additional butterfly and wild bee species were collected by conducting two further 5-min 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 standardised methods consistently applied across all three regions.

Post-hoc assessment: surrounding landscape, production economics and socialecological dimensions

In addition to the ecological variables measured *within* all the sites, we assessed the surrounding landscape using land-cover 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. 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). 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 area of extensive grassland in the surrounding and crop-type diversity, as well as amount of available pollen and nectar and pesticide use (following Hellwig et al. 2022). In total, we collected and produced data for 1916 km². All geographical data were processed in R (version 4.1.2; R Core Team) with the packages: sf (Pebesma & Bivand 2023; Pebesma 2018), terra (Hijmans 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, utilisation of forage, maintenance measures and financial support for the year 2022. Relevant stakeholders (farmers, administrative and NGO personnel) were approached to fill out questionnaires online or on the phone from January 2023 to March 2024. Furthermore, we developed a broader socialecological assessment based on stakeholder's perceptions of the type of restoration performed, the restoration goals and success, and the effect of the socialecological 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 socialecological context, we assessed if factors such as the climate conditions, land-use practices, stakeholder engagement or people's values towards 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 socialecological 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. In addition to asking the stakeholders directly responsible for the implementation of restoration in the post hoc sites, we assessed the public value of grassland restoration through surveys with the public across Germany. Our framework highlighted the diverse values driving stakeholder engagement, emphasizing their role in fostering inclusive and effective restoration efforts.

Real-world lab as a transdisciplinary approach

At the heart of *Grassworks'* socialecological research component are the real-world laboratories (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 contextual and normative, collaboratively designed to identify and address potential sustainability challenges (Wanner et al. 2018) – an endeavour pursued in each of the study regions. Establishing RWLs across the study regions required addressing different contextual factors and socialecological 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 socialecological 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 spatio-temporal variations in environmental and socio-economic 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 Centre emphasised the involvement of local stakeholders in restoration activities through citizen science programmes and the monitoring of participatory pilot actions. This approach would empower the community, increase 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 operationalise and track advances and changes in the RWLS, we focussed 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 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.

Synthesis and Integration

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). Bayesian belief networks are acyclic graphs representing networks of variables and their dependencies. The structure of our Bayesian belief network 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.

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 likelihood of success. Furthermore, all ecological data generated during the project will be uploaded to the German GFBio biodiversity data repository (https://www.gfbio.org/materials/) in accordance with FAIR principles (Wilkinson et al. 2016) and will be made publicly available following a two-year moratorium.

With the EU Restoration Law and national and the EU biodiversity strategies now firmly on the political agenda, the need for scaling up ecological restoration is greater than ever. Upscaling is not only a question of increasing the area that is restored, but also a socialecological endeavour 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, and creating tools and frameworks designed to inform and guide scalable and transferable restoration efforts. However, as with many transdisciplinary projects, *Grassworks* faced its own 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. These limitations highlight the continuing need for adaptive approaches and flexible frameworks to address the specific challenges of transdisciplinary and collaborative research projects.

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 socialecological system, integrating different values, practices, knowledge and goals, across different stakeholder groups. 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 socialecological components that drive restoration success. We consider that the outcomes from the socialecological *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 socialecological 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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References

Abson DJ, J Fischer, J Leventon et al. (2017) Leverage points for sustainability transformation. Ambio 46:30–39.

Bardgett , RD, JM Bullock, S Lavorel, P Manning, U Schaffnerset N Ostle, M Chomel, G Durrigan, E Frey, D Johnson, J Lavallee, G Le Provost, S Luo, K Png, M Sankaran, H Xiangzang, H Zhou, L Ma, R Webo, D Yong, L Yuanheng, S Hongxiao (2022) Combatting grassland degradation. *Nature Reviews Earth &Environment*, 2 (10). 720-735.https://doi.org/10.1038/s43017-021-00207-2

Bauer M, J Huber, J Kollmann (2024) Beta diversity of restored river dike grasslands is strongly influenced by uncontrolled spatio-temporal variability. J Vegetation Science 35:e13293.

Ben-Othmen A, Ostapchuk M. (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

Bergmann M, N Schäpke, O Marg et al. (2021)Trandisciplinary sustainability research in real-world labs: success factors and methods for change. Sustainability Science https://doi.org/10.1007/s11625-020-00886-8

Bengtsson J, JM Bullock, B Egoh, C Everson, T Everson, T O'Connor, PJ O'Farrell, HG Smith (2019) Grasslands—more important for ecosystem services than you might think. Ecosphere Volume 10(2) e02582

Blickensdorfer L, M Schwieder, D Pflugmacher, C Nendel, Erasmi, P Hostert (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 the Environment 269 112831.

Broeckhoven N and A. Cliquet (2015) Gender and Restoration Ecology: time to connect the dots. Restoration Ecology 23, 6, 729–736.

Brudvig LA (2017) Toward prediction in the restoration of biodiversity. Journal of Applied Ecology doi: 10.1111/1365-2664.12940.

Bucharova A, Lampei C, Conrady M, E May, J Metheja, M Meyer, D Ott (2022) Plant provenance affects pollinator network: Implications for ecological restoration. J Appl Ecol ;59:373–383. https://doi.org/10.1111/1365-2664.13866

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

Carlucci M, PHS Brancalion, RR Rodrigues, R Loyola, M Ciancaruso (2020) Functional traits and ecosystems services in ecological restoration. Restoration Ecology 28: 1372-1383.

Canessa C, Venus T. E, 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.

Choi Y., VM Temperton, EB Allen, A Grootjans, M Halassy, RJ Hobbs, MA NAeth and K Torok (2008) Ecological restoration for future sustainability. Ecoscience 15: 53-64.

Chytrý M., Tichý, L., Hennekens, S. M., Knollová, I., Janssen, J. A. M., Rodwell, J. S., Peterka, T., Marcenò, C., Landucci, F., Danihelka, J., Hájek, M., Dengler, J., Novák, P., Zukal, D., Jiménez-Alfaro, B., Mucina, L., Abdulhak, S., Aćić, S., Agrillo, E., … Schaminée, J. H. J. (2020). EUNIS Habitat Classification: Expert system, characteristic species combinations and distribution maps of European habitats. Applied Vegetation Science, 23(4), 648–675; https://doi.org/10.1111/avsc.12519

Drachenfels OV (2021) Kartierschlüssel für Biotoptypen in Niedersachsen unter Berücksichtigung der gesetzlich geschützten Biotope sowie der Lebensraumtypen von Anhang I der FFH-Richtlinie. Naturschutz und Landschaftspflege in Niedersachsen, Heft A/4, Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten-und Naturschutz.

De Groot RS, J Blignault, S van der Ploeg, J Aronson, T Elmqiust, J Farley (2013) Benefits of Investing in Ecosystem Restoration. Conservation Biology 27, No. 6, 1286–1293.

Dengler J and S Tischew (2018) Grasslands of western and northern Europe – between intensification and abandonment. In: Grassalnds of the World (edited by Squires, Dengler, Fend and Hua) International Standard Book Number 13: 13: 1-4987-9626-2

Dengler J, Janisova M, Török P, Wellstein C (2014) Biodiversity of Palaearctic grasslands: a synthesis. Agriculture Ecosystems and Environment 182: 1-14.

Dullau S, A Kirmer, Sabine Tischew, F Holz, MH Meyer, A Schmidt (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

Elias M, D Joshi, & R Meinzen-Dick (2021) Restoration for whom, by whom? A feminist political ecology of restoration. Ecological Restoration 39: 3-15.

Fernández-Manjarrés JF, S Roturier, & AG Bilhaut (2018) The emergence of the social-ecological restoration concept. Restoration Ecology, 26(3), 404-410.

Fischer J, M Riechers, J Loos, B Martin-Lopez, VM Temperton (2021). Making the UN Decade on Ecosystem Restoration a Social-Ecological Endeavour. Trends in Ecology & Evolution 36(1), 20-28, DOI: 10.1016/j.tree.2020.08.018.

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

Hellwig, N., Schubert, L. F., 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.

Helm A, M Zobel, AT Moles, R Szava-Kovats & M Partel (2015) Characteristic and derived diversity: implementing the species pool concept to quantify conservation condition of habitats. Diversity and Distributions 21:711-721.

Hess MCM, E. Buisson, H. Fontes, L Bacon, F Sabatier, F Mesléard (2020) Giving recipient communities a greater head start and including productive species boosts early resistance to invasion. Applied Vegetation Science

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(2), 357-383.

Jandt U, Bruelheide H, Jansen F, Bonn A, Grescho V, Klenke RA, Sabatini FM, Bernhardt-Römermann M, Blüml V, Dengler J (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

Knight M. L., Overbeck G. E. (2021) How much does it cost to restore a grassland? Restoration Ecology 29 (8), e13463. https://doi.org/10.1111/rec.13463

Leuschner C, K Wesche, S Meyer,B Krause, K Steffen, T Becker, & H Culmsee (2013). Veränderungen und Verarmung in der Offenlandvegetation Norddeutschlands seit den 1950er Jahren: Wiederholungsaufnahmen in Äckern, Grünland und Fließgewässern. In *Bericht. d. Reinard Tüxen Gesellschaft* (Vol. 25).

Leventon J; L Fleskens, H Claringbould, G Schwilch and R Hessel (2016) An applied methodology for stakeholder identification in transdisciplinary research. Sustainablity Science 11:763-775.

Lyons, KG, P Török, J-M Hermann, K Kiehl, A Kirmer, J Kollmann, GE Overbeck, S Tischew, EB Allen, JD Bakker, C Brigham, E Buisson, K Crawford, P Dunwiddie, J Firn, D Grobert, K Hickman, S Le Stradic, VM Temperton (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, DOI: 10.1016/j.gecco.2023.e02612

Martin DM (2017). Ecological restoration should be redefined for the twenty-first century. Restoration Ecology. *Vol. 25, No. 5, pp. 668–673*

MacPherson MP, EB Webb, A Raedeke, D Mengel, F Nelson (2018) A review of Bayesian belief network models as decision-support tools for wetland conservation: are water birds potential umbrella taxa? Biological Conservation 226

Messier C, K Puettman, R Chazdon, KP Andersson, VA Angers, L Brotons, E Filotas, R Tittler, L Parrott, SA Levin (2014) From Management to Stewardship: Viewing Forests as Complex Adaptive Systems in an Uncertain World. Conservation Letters 8:368-377

Montoya D, L Rogers and J Memmott *(2012)* Emerging perspectives in the restoration of biodiversity-based ecosystem services. Trends in Ecology and Evolution.

Nerlekar AN, Sullivan LL, Brudvig LA (2024) Grassland restorations must better foster forbs to facilitate high biodiversity. Restoration Ecology doi: 10.1111/rec.14214

NLWKN (Hrsg.) (2011): Vollzugshinweise zum Schutz der FFH-Lebensraumtypen sowie weiterer Biotoptypen mit landesweiter Bedeutung in Niedersachsen. – FFH-Lebensraumtypen und Biotoptypen mit höchster Priorität für Erhaltungs- und Entwicklungsmaßnahmen – Niedersächsische Strategie zum Arten- und Biotopschutz, Hannover

Pfadenhauer J (2001) Some Remarks on the Socio-Cultural Background of Restoration Ecology. Restoration Ecology Vol. 9 No. 2, pp. 220–229

Pfadenhauer J, Poschlod P & Buchwald R (1986). Überlegungen zu einem Konzept geobotanischer Dauerbeobachtungsflächen für Bayern. Teil I. *Berichte der Bayerischen Akademie für Naturschutz und Landschaftspflege*, 10, 41–60. Retrieved from https://www.zobodat.at/pdf/Ber-Bayer-Akad-f-Natursch-u-Landschaftspfl_10_1986_0041-0060.pdf

Pfadenhauer J (2001) Some Remarks on the Socio-Cultural Background of Restoration Ecology. Restoration Ecology 9: 220-229

Perring MP, TE Erickson, P Brancalion (2018) Rocketing restoration: enabling the upscaling of ecological restoration in the Anthropocene. Restoration Ecology doi: 10.1111/rec.12871

Shackelford N, RJ Hobbs, JM Bruger et al. (2013) Primed for Change: Developing Ecological Restoration for the 21st Century**.** Restoration Ecology Vol. 21, No. 3, pp. 297–304*.*

Shackelford N, RJ Hobbs, JM Burgar, TE Erickson, JB Fontaine, E Lalliberte, CE Ramalho, MP Perring, RJ Standish (2013) Primed for Change: Developing Ecological Restoration for the 21st Century. Restoration Ecology 21: 297-304.

Shackelford N BB Paterno, DE Winkler et al. (2021a) Drivers of seedling establishment success in dryland restoration efforts. Nature Ecology and Evolution. VOL 5: 1283–1290

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

Socher SA, Prati D, Boch S, Müller J, Baumbach H, Gockel S, Hemp A, Schöning I, Wells K, Buscot F, Kalko EKV, Linsenmair KE, Schulze E-D, Weisser WW, Fischer M (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(2) 126-136.

Schäpke N, F Stelzer, G Caniglia et al. (2018) Jointly experimenting for transformation? Shaping real-world laboratories by comparing them. GAIA-Ecological Perspectives for Science and Society, 27(1), 85-96.

Schäpke N, R Beecroft, M Wanner, F Wagner, R Rhodius, P Laborgne and O Parodi. (2021) Gaining deep leverage? Reflecting and shaping real-world lab impacts through leverage points. Gaia 33:116-124.

Shipley JR, ER Frei, A Bergmaini, N Pichon, et al. (2019) Agricultural practices and biodiversity: Conservation policies for semi-natural grasslands in Europe. Current Biology 34: 747-771.

Schwieder, M Wesemeyer, D Frantz, K Pfoch, S Ersami, J Pickert, C Nendel, P Hostert (2022) Mapping grassland mowing events across Germany based on combined Sentinel-2 and Landsat 8 time series. Remote Sensing of the Environment 269: 112795.

Squires VR, J Dengler, H Feng, L Hua (2018) Grasslands of the World: Diversity Management and Conservation. CRC Press, 42 pages, International Standard Book Number-13: 1-4987-9626-2

Staude IR, J Segar VM Temperton, BO Andrade, M de Sá Dechoum, EWA Weidlich, GE Overbeck (2023). Prioritize grassland restoration to bend the curve of biodiversity loss. Restoration Ecology, 31 (5), e13931, DOI: 10.1111/rec.13931.

Stelzenmüller V; HO Fock, A Gimpel, H Rambo, R Diekmann, WN Porbst, U Callies, F Bockelmann, H Neumann, I Kröncke (2015) Quantitative environmental risk assessments in the context of marine spatial management: current approaches and some perspectives. ICES Journal of Marine Science 72(3), 1022–1042.

Tedesco AM, S López-Cubillos, R Chazdon et al. (2023) Beyond ecology: ecosystem restoration as a process for social-ecological transformation. Trends in Ecology and Evolution Vol. 38, No. 7.

Tischew S, A Baasch, MK Conrad, A Kirmer (2008) Evaluating Restoration Success of Frequently Implemented Compensation Measures: Results and Demands for Control Procedures. Restoration Ecology

Tivian. (2024). Online survey software: Surveys made easy with Unipark Tivian XI GmbH. https://www.unipark.com/en/

Traveset A, Lara-Romero C, Santamaria S, Escribano-Avila G, Bullock JM, Honnay O, Hooftman DAP, Kimberly A, Krickl P, Plue J, Poschlod P, Cousins SAO (2023) Effect of green infrastructure on restoration of pollination networks and plant performance in semi-natural dry grasslands across Europe. J. Applied Ecology. DOI: 10.1111/1365-2664.14592

Wanner M, A Hilger, J Westerkowski, M Rose, F Stelzer & N Schäpke (2018) Towards a Cyclical Concept of Real-World Laboratories: A Transdisciplinary Research Practice for Sustainability Transitions. disP –The Planning Review 54(2): 94-114.

Waldén E & R Lindborg (2018) Facing the future for grassland restoration – What about the farmers? Journal of Environmental Management 227: 305-312.

Wesche K, Kruase 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.

Wilkinson (2016) Comment: The FAIR Guiding Principles for scientific data management and stewardship- Nature Scientific Data 3:160018 | DOI: 10.1038/sdata.2016.18

Wortley L, JM Hero & M Howes (2013) Evaluating Ecological Restoration Success: A Review of the Literature. Restoration Ecology Vol. 21, No. 5, pp. 537–543

Zedler J (2007) Success: An Unclear, Subjective Descriptor of Restoration Outcomes. Ecological Restoration 25 (3).

Zerbe S (2023) Restoration Economy: Costs and benefits. In: Restoration of Ecosystems- Bridging Nature and Humans. Springer Spektrum, Berlin, Heidelberg.

Tables

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	

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). *Restoration method* abbreviations: MgA = management adaptation; DiH = direct harvesting, ReS = regional seed mixture, CuS = cultivar seed mixture.

Variable	***North***	***Centre***	***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*

Table 3. Key differences in characteristics and methodological approaches of Real World Laboratories (RWLs) in the *Grassworks* project

Real-World Laboratory (RWL) Characteristics	**RWL North**	**RWL Centre**	**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
Cooperation partner	Gifhorn County, Aktion Fischotterschutz e., and Biohof Flegel KG	Heimat and Naturschutzverein Hainrode e. V.	Gauting Municipality
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. Species-rich 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 ploughing, gravel extraction, and dyke construction.
Demonstration site(s)	Long-term grassland experiment testing potential of priority effects (POEM project, Alonso-Crespo et al. in revision) 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 siteas 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 2 densities and with 4 soil preparation methods (topsoil removal, grubbing, rotary tilling, management adaption/no preparation); Included 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

Figures

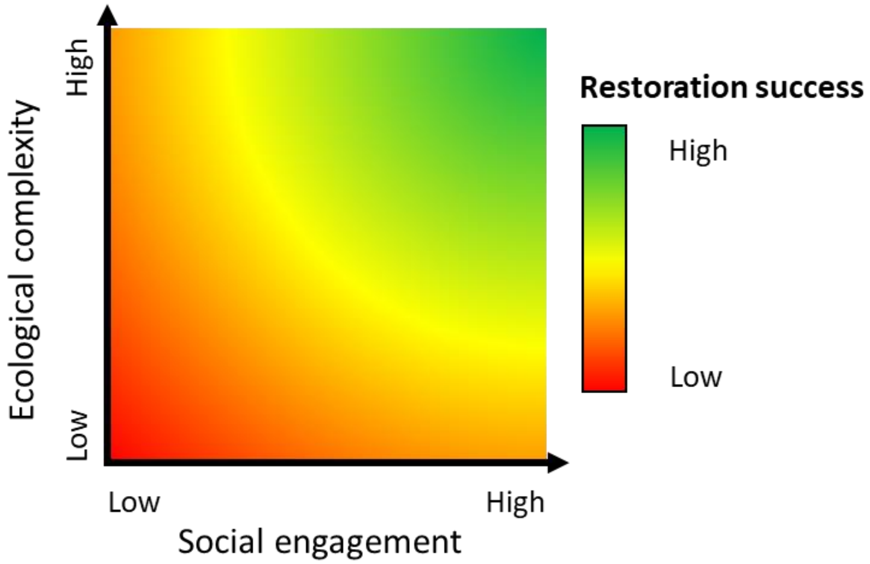


Figure 1. Our central hypothesis is that the overall socialecological success of restoration relates to the extent to which both ecological and stakeholder complexity are considered in the restoration process. We hypothesise that the higher the ecological complexity and social engagement (stakeholder diversity/inclusion) are, the higher the restoration success will be. Our combination of ecological, socialecological and economic data within *Grassworks* allows us to test this hypothesis. The success of restoration is

shown as a sequence of colours, 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.

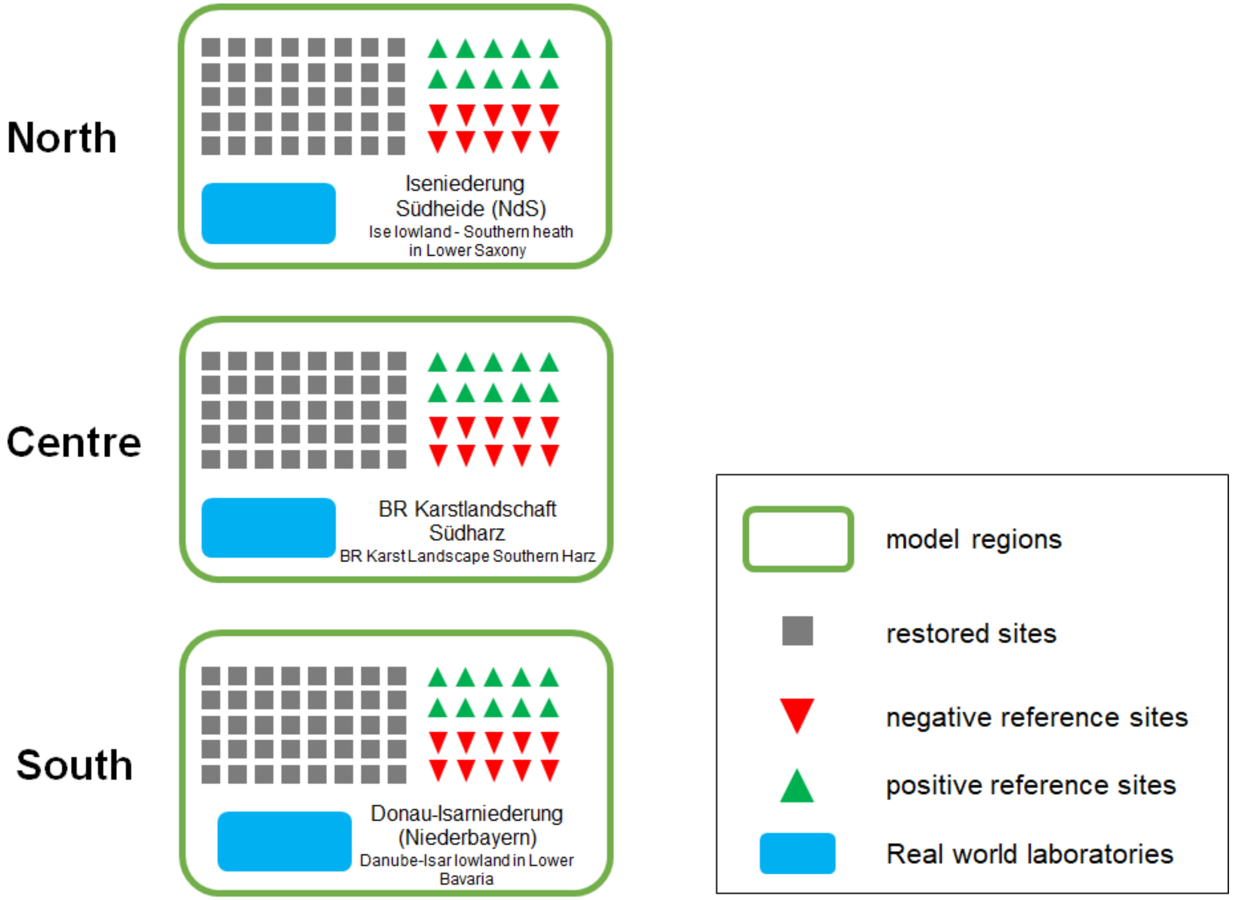


Figure 2. The *Grassworks* research approach for assessing grassland restoration success using a natural landscape experiment approach for the post-hoc sampling and real-world laboratories (RWL). We compared three regions from north to south in Germany. Within each region we did a post-hoc assessment of approximately 40 already restored grasslands as well as ten positive and ten

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 Centre) and an online forum was established in the South. BR = biosphere reserve.

Figure 3. Approach to assess ecological parameters at each of the restored or reference sites in the post-hoc assessment in three regions (Figure 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 were sampled four times over a growing season compared to vegetation once.

Boxes

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 (Figure 2) we decided to take the availability of different grassland types in the real landscape within our three larger regions (North, Centre, South) into account, and did not stringently balance every factor that we considered important for restoration outcomes (see Table 1 as well as Table 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 Centre, 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 (Table 1, Table 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, 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 amongst 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. Whilst 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 and reference sites.

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 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. 2021b) 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. 2019). For an overview of the use of contemporary, historical or future references sites across local to regional scales see Shackelford et al. (2021).

In *Grassworks*, we used contemporary and local references sites, both negative and positive. We chose classical contemporary positive references 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. 2023 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 visualisation 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 2021; *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 (Drachenfels 2021, regional lists of donor sites (Spenderflächenkataster: https://www.spenderflaechenkataster.de/startseite), Landesamt für Umweltschutz (LAU) in Saxony-Anhalt (2019; 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).

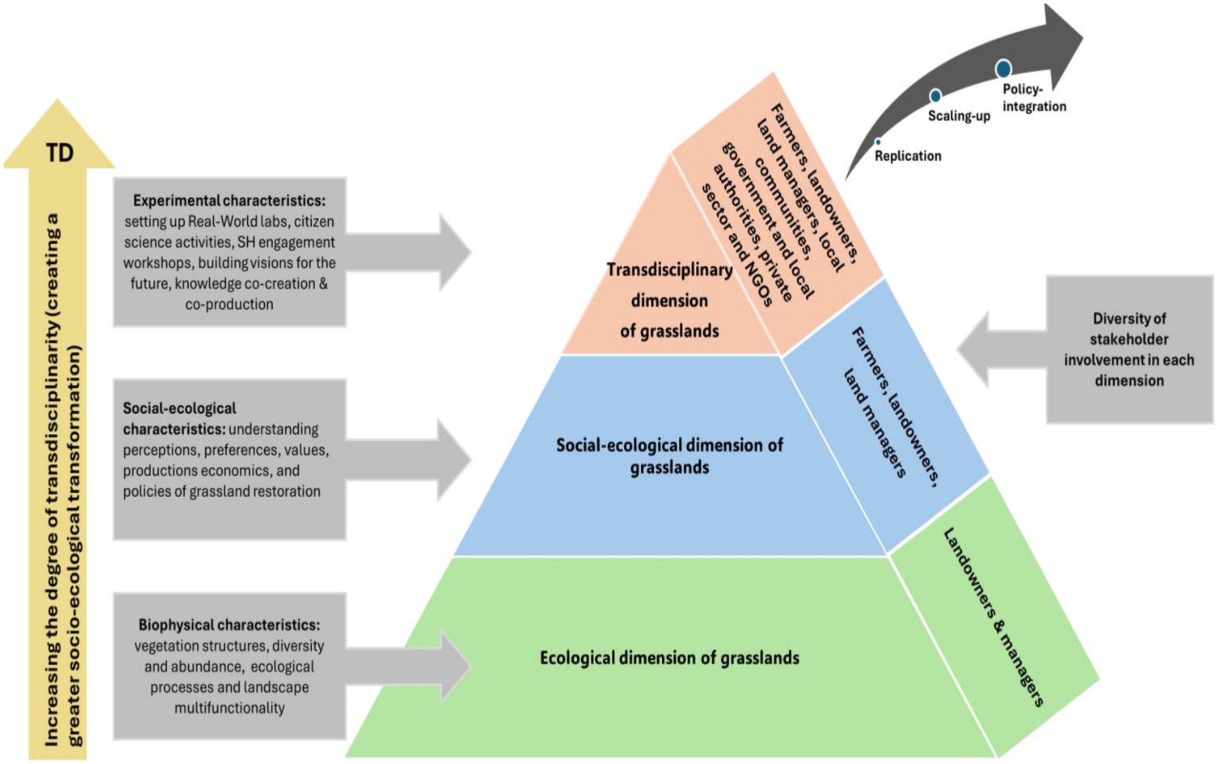
Our approach has the strength that our restored and reference sites represent a gradient of restoration intensity across three different regions in Germany. The challenge however, consisted of finding both positive and negative references sites. Initially, we had hoped to be able to pair the restored 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 realisation during the process of site selection during the planning of the post-hoc site analysis.

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 socialecological and finally to the transdisciplinary dimensions of grassland restoration, the diversity of stakeholders and the potential for socialecological transformation increase. The transdisciplinary dimension integrates experimental approaches such as real-world laboratories (RWL), 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.



A holistic perspective on social-ecological system dimensions within the Grassworks project

Socialecological 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 socialecological 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. 2021). There are indeed multiple levels of interdisciplinarity both within more natural science focused research projects but also within socialecological research 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 standardisation 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.

Supporting Information

Table S1: Braun Blanquet Plant Cover Scale**.** We used the following plant cover scale in *Grassworks*, adapted from the original Braun-Blanquet scale, for vegetation surveys on 4 m^2 quadrats. This scale follows (Pfadenhauer et al., 1986) but has some adapted cover and mean coverages.

Cover class	Cover [%]	Mean cover [%]
r	< 0.1	0.1
+	0.1 - 1	0.5
1a	1- 3	2
1b	3 -5	4
2a	5 -15	10
2b	15 - 25	20
3	25 - 50	37.5
4	50 - 75	62.5
5	75 - 100	87.5

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.

Category	*Questions / Possible answers*
(A) Contact	Name

	Name of the farm or organisation Address Telephone number E-mail address Would you like us to contact you for future research in the field of grassland restoration? How large is the area that has been restored? What is the water balance of the area? It is very relevant for us to assess the location of the restored area in the landscape. We do this using aerial photographs or satellite images. Please provide information on the location of the area. You are welcome to copy the coordinates from google maps or other software here.
(B) Owner	Who is the owner of the restoration area (or reference site)?
(C) Objectives	Establishment of species-rich grassland Habitat network Erosion control Carbon sequestration Further objective 1 Further objective 2
(D) Success of the objectives	Establishment of species-rich grassland Habitat network Erosion control Carbon sequestration Further objective 1 Further objective 2
(E) Utilization before restoration	How was the area used before the restoration? How long has it been since the area was restored?

(F) Preparation prior to restoration	Scrub clearance: Have woody plants been removed? Soil Nutrient Depletion: Have nutrients been removed from the nutrient-rich (arable) soil, e.g. by growing crops without fertiliser? Creation of open soil: Has the area been tilled, e.g. by tilling/grubbing, rotovating or ploughing?
(G) Restoration method	Wild plants from certified propagation (regional seed mixture; Regiosaatgut in German) Direct harvesting methods such as green hay transfer Cultivar seed mixtures (Regelsaatgut in German) Other Is there an area nearby where the grassland develops without sowing and without fertilisation? How is the area managed or maintained? Does monitoring take place to document changes in the area?
(H) Funding set-up	How or under which programme were the area's restoration measures funded? Other
(I) Funding for management	How is the ongoing maintenance of the area and follow-up management funded? Other
(J) Control	Who has checked whether the planned restoration measures are being implemented correctly?

Table S3: Overview of data sources for retrieving remote sensing data on surrounding landscape around restored grassland sites.
Strg + click to open links

Federate State	**Used Data**	**Data-sources**
Schleswig-Holstein	Official Real Estate Cadastre Information System (ALKIS)	ALKIS: Landesamt für Vermessung und Geoinformation Schleswig-Holstein (https://geodaten.schleswig-holstein.de/gaialight-sh/_apps/dladownload/dl-alkis.html) Biotope Maps: Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein (https://opendata.schleswig-holstein.de/dataset/biotopkartierung).
Lower Saxony	German official Digital Landscape Model Base (Basic DLM) + Integrated Administration and Control System (IACS) + OpenStreetMap	Basic DLM retrieved via Thünen Institute for Biodiversity, Braunschweig. IACS: LEA Portal (https://sla.niedersachsen.de/landentwicklung/LEA/). OSM Data via R-Package „osmdata“.
Hamburg	Official Real Estate Cadastre Information System (ALKIS)	ALKIS: Landesbetrieb Geoinformation und Vermessung Hamburg (https://metaver.de/trefferanzeige?docuuid=DC71F8A1-7A8C-488C-AC99-23776FA7775E). Biotope Maps: https://suche.transparenz.hamburg.de/dataset/biotopkataster-hamburg10?forceWeb=true
Saxony-Anhalt	Official Real Estate Cadastre Information System (ALKIS)	ALKIS: Landesamt für Vermessung und Geoinformation Sachsen-Anhalt (LVermGeo) (via personalized Download). Biotope Mapping Data: Landesamt für Umweltschutz Sachsen-Anhalt (LAU) (via personalized Download).

Bavaria	Official Real Estate Cadastre Information System (ALKIS) Biotope Mappings.	ALKIS: Bayerische Vermessungsverwaltung (https://geodatenonline.bayern.de/geodatenonline/) Biotope Maps: Bayerisches Landesamt für Umwelt (https://www.lfu.bayern.de/natur/biotopflaechen_sachdaten/index.htm)
Brandenburg	Official Real Estate Cadastre Information System (ALKIS)	ALKIS: Landesvermessung und Geobasisinformation Brandenburg (https://data.geobasis-bb.de/geobasis/daten/alkis/Vektordaten/shape/)
Mecklenburg-West Pomerania	Official Real Estate Cadastre Information System (ALKIS) Biotope Mappings.	ALKIS: Landesamt für innere Verwaltung - Amt für Geoinformation, Vermessungs- und Katasterwesen Mecklenburg-Vorpommern (via personalized download). Biotope Maps: Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg Vorpommern (via CD).