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A new Restoration Intensity Index: Understanding how restoration methods and follow-up management control grassland recovery

Annika Schmidt [a,*], Felix May [b], Regina Neudert [c], Anita Kirmer [a], Johannes Kollmann [d], Vicky M. Temperton [e], Christin Juno Laschke [e], Line Sturm [a], Miriam Wiesmeier [d], Alina Twerski [a,e]

[a] Nature Conservation and Landscape Planning, Anhalt University of Applied Sciences, Strenzfelder Allee 28, 06406 Bernburg, Germany
[b] Theoretical Ecology, Institute of Biology, Freie Universität Berlin, Königin-Luise-Straße 2/4, Gartenhaus, 14195 Berlin, Germany
[c] Institute of Botany, Faculty of Law and Economics, Greifswald University, Soldmannstraße 15, 17489 Greifswald, Germany
[d] Chair of Restoration Ecology, School of Life Sciences, Technical University of Munich, Emil-Ramann-Straße 6, 85354 Freising, Germany
[e] Institute of Ecology, Leuphana University Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany

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ABSTRACT

Restoration can help to counteract biodiversity loss and to secure ecosystem functioning. In grassland ecosystems, a variety of restoration methods have been applied. Studies assessing their effectiveness often include categorical comparisons that ignore variation in restoration intensity, especially within one method. To account for the complexity of grassland restoration, a continuous metric that assesses restoration intensity would facilitate deeper analyses which may identify leverage points for successful restoration. Therefore, we propose a continuous multi-dimensional Restoration Intensity Index (RII) to quantify the degree of intervention and the follow-up management. The suggested RII includes the components (i) site preparation intensity, (ii) species introduction quality, and (iii) management appropriateness. We evaluated the RII using vegetation data from 77 restored grasslands covering a gradient in soil moistures and restoration methods across three regions in Germany. The restoration methods included adapted management, cultivar or regional seed mixtures, and transfer of directly harvested seed material. The RII was positively correlated with the overall and target plant species richness and Hill-Shannon diversity. Furthermore, species introduction quality and thus seed origin and seed composition were key components to promote total and target plant species richness, and to increase the proportion of forb cover. The time since restoration intervention did not influence grassland recovery, except in interaction with site preparation intensity. Thus, the RII is a promising tool enabling comparison of complex measures. It indicates that increased efforts in restoration intervention and follow-up management are decisive for restoring and maintaining species-rich grasslands in the long-term.

1. Introduction

Worldwide, up to 40% of the terrestrial surface is covered by grasslands (Petermann and Buzhdygan, 2021). These ecosystems harbour a high biological diversity (Habel et al., 2013; Dengler et al., 2014) and provide many ecosystem services (Bengtsson et al., 2019; Petermann and Buzhdygan, 2021; Lange et al., 2023; Klaus et al., 2024). Despite their conservation value, species-rich grasslands in Europe are threatened due to land-use intensification, abandonment, or conversion (Dengler and Tischew, 2018; Schils et al., 2022; Pazúr et al., 2024). For Germany, comparisons with historical data showed that species richness of grasslands declined over the past 50–75 years (Wesche et al., 2012; Diekmann et al., 2019; Jandt et al., 2022). Consequently, not only conservation of the remaining species-rich grasslands but also restoration of degraded sites are urgently needed to bend the curve of biodiversity loss, especially for threatened species (Staude et al., 2023). To restore grasslands, actors from agriculture or conservation apply a range of methods, depending on former land use, legal requirements, and site

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* Corresponding author at: Anhalt University of Applied Sciences, Strenzfelder Allee 28, 06406 Bernburg, Germany.
E-mail addresses: annika.schmidt@hs-anhalt.de (A. Schmidt), felix.may@fu-berlin.de (F. May), regina.neudert@uni-greifswald.de (R. Neudert), anita.kirmer@hs-anhalt.de (A. Kirmer), johannes.kollmann@tum.de (J. Kollmann), vicky.temperton@leuphana.de (V.M. Temperton), line.sturm@hs-anhalt.de (L. Sturm), miriam.wiesmeier@tum.de (M. Wiesmeier), alina.twerski@hs-anhalt.de (A. Twerski).

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conditions (Slodowicz et al., 2023). Sowing of seed mixtures, transfer of directly harvested seed material, or adaptation of management are the most common approaches (Nolan et al., 2021; Dellicour et al., 2023; Köhler et al., 2023; Slodowicz et al., 2023). Despite much practical experience and scientific research in grassland restoration, restoration projects do not consistently reach the goal of recovery of the desired communities (Conrad and Tischew, 2011; Brudvig et al., 2017; Jones et al., 2018). Thus, in-depth and integrated post-hoc analyses of already implemented restoration projects are required to increase the understanding of underlying processes, accuracy in predicting the outcomes of restoration projects and to derive implications for practice (Wortley et al., 2013; Brudvig et al., 2017; Resch et al., 2021; Brudvig and Catano, 2024).

All restoration methods manipulate ecological filters to foster the reassembly of target plant communities (Funk et al., 2008). These ecological filters drive the occurrence of species in a community through the species pool (‘dispersal filter’), abiotic conditions (‘abiotic filter’), and interspecific interactions (‘biotic filter’) (Funk et al., 2008; Funk, 2021). Differences in restoration success may be explained by different methods manipulating these filters in different ways and with varying intensity. For example, an impoverished local or regional plant species pool, e.g., due to degraded soil seed banks, poor seed dispersal, and habitat isolation (Poschlod et al., 2009; Krickl, 2022), can be overcome by seeding or transferring seed-rich material (Shaw et al., 2020; Freitag et al., 2021; Nolan et al., 2021; Slodowicz et al., 2023). However, there is considerable variation in which species are introduced by these methods. Seed mixtures, for example, can differ in origin, the species number, and forb-to-grass ratio. Thus, the composition and quality of introduced plant material rather than the method itself, may play a more important role for restoration success.

Unsuitable abiotic site conditions can also impede restoration outcomes. In this case, additional modification of environmental conditions, for example, by reducing the soil nutrient loads, can increase establishment of the desired community (Freitag et al., 2021). Interspecific competition can be controlled in two ways. Competition from existing vegetation is reduced by sward disturbance, e.g., harrowing, thus providing a suitable seed bed for germination and establishment (Kiehl, 2010; Schmiede et al., 2012; Durbecq et al., 2023). Therefore, plant diversity increases when sowing and soil disturbance are combined, while seeding in an intact grass sward is only marginally successful (Freitag et al., 2021). After species introduction, or if no species were introduced, interspecific competition can be regulated by resuming or adapting site management. It is well known that different types of management, e.g., mowing or grazing, along with their intensity and appropriateness, control vegetation development (Poschlod et al., 2009; Elias and Tischew, 2016; Nolan et al., 2021) and are specific to each vegetation type. During restoration, overcoming these ecological filters can therefore be classified into the intervention components of species introduction quality (‘dispersal filter’), site preparation intensity (‘abiotic and biotic filter’) and management appropriateness (‘biotic filter’). In addition, it can be assumed that re-establishing a species-rich vegetation is a challenge that can take decades (Öster et al., 2009a; Prach et al., 2014; Buisson et al., 2022). During this time, effects of initial restoration can be overridden by follow-up management (Tölgyesi et al., 2021; Sommer et al., 2023), and the importance of the restoration components may change with time (Funk, 2021).

There are many studies that compare restoration intervention methods to assess the establishment of target plant species and communities (e.g., Slodowicz et al., 2023), but most are based on binary comparisons among categorical methods and often ignore the variation in restoration intensity within methods. Analyzing the effects of the intensity of restoration, rather than comparing distinct methods, would allow a detailed investigation of general patterns and facilitate the identification of leverage points for successful restoration (Abson et al., 2017). Recommendations derived from an assessment of restoration intensity could overcome legal or regional restrictions on methods (i.e., availability of donor sites or suitable seed mixtures) and ensure long-term restoration success at both local and landscape level. So far, only few publications have focused on ‘restoration intensity’ (e.g., Jones et al., 2018; Chazdon et al., 2024), and most studies have severe limitations, since they refer to a certain region or vegetation type (McFarlane et al., 2023), restoration method (Kardol et al., 2008), or used only few intensity categories (Schnoor et al., 2015; Resch et al., 2021; McFarlane et al., 2023; Klaus et al., 2016). Since categories may blur the transitions in the restoration gradient and thus make it difficult to identify parameters that control restoration outcomes, a continuous metric would help to address this problem. Similar concepts already exist and have been proven to be beneficial, e.g. the Land Use Intensity Index (LUI, *sensu* Blüthgen et al., 2012), which integrates the intensity of different land use practices in grasslands, namely grazing, mowing, and fertilization. Therefore, an index for quantifying ‘restoration intensity’ that enables comparisons across multiple methods, regions, and time would facilitate the understanding and improve the prediction of long-term restoration success.

This study proposes a multi-dimensional continuous ‘Restoration Intensity Index’ (RII), and applies it to a large data set of restored grasslands. The suggested RII consists of three components, i.e., site preparation intensity, species introduction quality, and management appropriateness, and thus accounts for the methods applied in grassland restoration and follow-up management. Depending on the objective, the RII can be used as a single index or its components can be analysed separately to assess their individual contributions. In addition, based on the assumption that the primary objective of restoration, particularly at higher levels of restoration intensity, is to achieve a high degree of recovery, we evaluated the performance of both the RII and its three independent components in relation to restoration outcomes across a wide range of restored grasslands covering different soil moisture levels across three regions in Germany (Temperton et al., 2025). We analyze whether these relationships change with time since restoration. We hypothesize a positive relation between restoration intensity and grassland recovery. Furthermore, we expect that the importance of the individual components changes over time, with the effects of management increasing while those of soil preparation and species introduction decrease. Finally, we suggest and discuss applications and adaptations of the RII.

2. Material and methods

2.1. *The test data set*

Within the collaborative project GRASSWORKS (www.grassworksprojekt.de/en/), researchers in ecology, social sciences, economics, and governance cooperated with the German Association for Landcare Management (DVL) to understand how and under what conditions grassland restoration is successful (Temperton et al., 2025). To achieve this goal, restored sites were compared with positive (‘non-degraded’) and negative (‘degraded’) reference sites across three regions in the North, Centre, and South of Germany. In each region, at least 40 restored sites were selected (121 in total) that covered a wide range of soil moisture levels (dry: Festuco-Brometea, Koelerio-Corynephoretea; fresh: Arrhenatheretalia elatioris; moist: Molinietalia caeruleae; community names follow Leuschner and Ellenberg, 2017), four restoration methods (i.e., sowing cultivars or regional seed mixtures, management adaptation, or transfer of direct harvested material), previous land-use history (arable land or degraded grassland), management types (mowing, grazing, or both), time since restoration (2–30 years), and land-use intensities. Furthermore, 33 positive reference sites were chosen that cover a similar range of soil moisture.

Vegetation was sampled along a single 5 m × 200 m transect at each site, in the years 2022 or 2023. This transect was divided in four 50-m sections (‘sub-transects’) and for each section, one vegetation survey was made on 4 m^2 (2 m × 2 m) quadrats (positioned at points derived at

Table 1
Weighting of site preparation intensity, i.e., component *Site* of the suggested Restoration Intensity Index. *Site* was grouped according to the environmental filter addressed by the intervention (Funk et al., 2008).

Establishment filter	Site preparation intensity	Restoration technique	Weighting
None	No intervention	No activity	0.00
Abiotic	Creation of favorable environmental conditions for restoration	Raising groundwater level	0.50
		Nutrient reduction	0.50
Biotic	No sward modification	Mowing	0.25
		Mulching	0.25
	Low sward modification	Shrub removal	0.50
		Rolling	0.50
	Moderate sward modification	Grubbing	0.75
		Rotary tilling/heifers	0.75
		Harrowing	0.75
	Major sward modification	Topsoil removal	1.00
		Deep ploughing (>0.7 m)	1.00

Table 2
Weighting of species introduction methods in grassland restoration (component *Spec*). Forbs include all forb and legume species.

Level	Origin, seed propagation	Number of forb species in seed mixture	Proportion of forb seed in total seed weight	Weighting
No seeds added				0.00
Cultivar seed mix, forb-poor	Non-regional	<50%		0.20
Cultivar seed mix, forb-rich	Non-regional	>50%		0.40
Regional seed mix, forb-poor	Regional	<30 species	AND < 50%	0.60
Regional seed mix, forb-rich	Regional	>20 species	AND > 50%	0.80
Directly harvested seeds	Regional	Unknown, but expected to be highest	Unknown, but expected to be highest	1.00

random along the 50-m stretch), resulting in four quadrats per site and a total vegetation sampling area of 16 m^2. Within each quadrat we assessed species presence as well as their cover using a modified Braun-Blanquet scale (Table S1); nomenclature followed Buttler and Thieme (2018). The data on restoration intervention and management was obtained through surveys and interviews with farmers. Due to some incomplete data for the three components of RII, the final data set included 77 sites (26 northern, 26 central and 25 southern region).

2.2. Calculation of the Restoration Intensity Index

The RII assessed the overall intensity of restoration interventions based on the contribution of three key components, i.e., site preparation intensity (*Site*), species introduction quality (*Spec*) and management appropriateness (*Mgmt*). The components were selected based on numerous studies, referred to as the 'dispersal filter' (species introduction), 'abiotic filter' (site preparation) and 'biotic filter' (site preparation and management) according to Funk et al. (2008), Temperton et al. (2013), and Funk (2021).

2.2.1. Site preparation intensity

Site preparation intensity (*Site*) included various methods and their frequency to prepare suitable abiotic and biotic conditions prior or shortly after species introduction. This component measures to what extent vegetation and/or soil were altered or disturbed with technical measures to facilitate restoration success. The applied methods depended on land-use history and the target vegetation. Mulching, mowing, and shrub removal were conducted to clear overgrown grasslands prior to soil preparation or the establishment of a pasture. Soil disturbance and seed-bed preparation were performed by grubbing, tilling, harrowing, ploughing, or topsoil removal. After seeding, rolling was often applied to improve soil contact of seeds, thus promoting germination and increasing establishment (Shaw et al., 2020).

Weighted by the intensity of the soil disturbance, we assigned a value between 0.00 and 1.00 to each method (Table 1), i.e., no site preparation (0.00), no sward modification but regulation of vegetation cover (0.25, e.g., mowing), creation of favorable environmental conditions for restoration (0.50, soil nutrient reduction by cultivation of crops without fertilization or raising groundwater level for restoring wet grassland types), moderate modification of the vegetation cover (0.75, e.g., grubbing), and major disturbance of the sward (1.00, e.g., deep ploughing).

The *Site* component was calculated by adding the weighted values for all methods that had been applied at the site. For example, if site *i* was mown once, grubbed twice and rolled after sowing, this resulted in *Site*$_i$ $= 0.25 + (2 \times 0.75) + 0.50 = 2.25$.

2.2.2. Species introduction quality

The species introduction component (*Spec*) reflects different qualities of plant introduction based on the origin and propagation of the introduced species and the share of forbs included (Table 2). These factors have a significant impact on the establishment of characteristic grassland communities (Kiehl, 2010; Freitag et al., 2021). We therefore defined levels for weighting their quality, depending on whether the introduced seeds were cultivars, non-regional plants, or native wild species of regional origin; further, the number of forb species and the proportion of forbs in the total seed weight were included (Table 2).

Moreover, we considered the most commonly applied methods of seed introduction, i.e., seed mixtures, green hay, or dry hay. Regional seed mixtures were given higher values than cultivar mixtures, because many studies confirm that the regional ecotypes from regional propagation are better adapted to the prevailing environmental conditions than commercial cultivars (Conrad and Tischew, 2011; Sengl et al., 2017; Bucharova et al., 2019; McFarlane et al., 2023). Therefore, site-specific wild seed mixtures have a higher chance of establishment success than cultivar mixtures (Schmidt et al., 2020; Freitag et al., 2021). Grass species were not considered in the calculation of introduced plant diversity because most grasses tend to dominate (especially on nutrient-rich sites) and compromise restoration success (Nerlekar et al., 2024). In cases where the transfer of directly harvested material was performed, it is difficult to determine the precise number of species transferred. As these methods are capable of transferring entire plant communities (Rosenthal and Hölzel, 2009; Kiehl, 2010; Garrouj et al., 2024), they have been assigned the highest value. Furthermore, the transfer of green hay or threshed material from a nearby donor site is an effective method for establishing species from the local gene pool that are already adapted to the site, including rare, vegetatively reproducing, or difficult to propagate plants that are not available in commercial seed mixtures

(Kirmer and Tischew, 2006; Kiehl, 2010; Török et al., 2011). Management adaptation was the only method where no species were introduced.

Each species introduction method was given a value between 0.00 and 1.00, where 0.00 means that no species have been introduced, and 1.00 means a very high quality of species introduction. The *Spec* component was calculated by summing up the weighted values for all the methods that had been applied on a site. For example, if species had been introduced to site *i* by transferring harvested material and sowing ten additional native forbs of regional origin, the resulting component was $Spec_i = 1.00 + 0.80 = 1.80$.

2.2.3. Management appropriateness

The grazing and/or mowing regime can promote the establishment of characteristic plant species, and thus accelerate recovery success (Török et al., 2011; Dengler et al., 2014). Thus, the management component (*Mgmt*) focussed on the appropriateness of follow-up management rather than its intensity. It was assessed differently depending on the soil moisture level. Calculation of the management component was based on an adapted Land Use Intensity Index (LUI *sensu* Blüthgen et al., 2012), which incorporates mowing and grazing intensities.

It was calculated in three steps:

(1) Calculation of the intensity of management, considering the soil moisture level:

$$Intensity_i = \left(f_{hydro} \times M_i\right) + G_i,$$
$$with\ f_{dry} = 0.25,\ f_{fresh} = 0.5,\ f_{moist} = 0.75$$

(2) Calculation of the deviation between the management intensity of the site and that of positive references, considering the soil moisture level:

$$Deviation_i = \frac{\left(Intensity_i - Intensity_{p-hydro}\right)}{Intensity_{p-hydro}}$$

(3) Standardization and calculation of management appropriateness component:

$$Mgmt_i = 1 - \left|\frac{(Deviation_i - Deviation_{min})}{(Deviation_{max} - Deviation_{min})}\right|$$

M_i refers to the frequency of mowing interventions per year, and G_i is the grazing intensity, corresponding to the stocking rate (livestock units ha^{-1}; standardized over a grazing period of 365 days), on site *i* for a given year (2022 in this study). It comprised grazing by cattle, horses, sheep, or goats, all of which were converted to ‘livestock units’ as outlined by Fischer et al. (2010). Combining mowing and grazing to the overall management intensity of site *i* ($Intensity_i$) requires both to be set to the same scale. For this purpose, we converted mowing events into livestock units, taking into account the soil moisture level by weighting each mowing event with a factor according to the expected amount of biomass provided for livestock (f_{hydro}). To analyze if the applied management was appropriate from a restoration perspective, the difference between the given management on site *i* ($Intensity_i$) and the optimal management derived from the positive reference sites *P* ($Intensity_{p\text{-}hydro}$) was calculated and then standardized relative to the mean of the positive reference sites of the respective soil moisture level ($Deviation_i$). We decided to use actual sites as the reference framework since several studies postulated that historical phytosociological data may no longer be pertinent in our present-day ecological and socio-economic context (Jones et al., 2018; Dellicour et al., 2023). Mean values for mowing, grazing, and the overall management intensity of the positive references per soil moisture level ($Intensity_{p\text{-}hydro}$) for the year 2022 can be found in Table S2. If $Deviation_i = 0$, this indicates that the management was in an optimal state, according to the management performed in the study area. Negative values refer to management that was too extensive, while positive values refer to management that was too intensive compared to the reference sites. Finally, $Mgmt_i$ was calculated according to Eq. (3) as 1.00 minus the absolute value of min-max-scaled deviation of site *i* ($Deviation_i$). Taking the absolute values and standardization by min-max scaling results in values ranging between 0.00 and 1.00, where 0.00 corresponds to the most appropriate management and 1.00 to the least appropriate, while the linear relationships between the data points are preserved. To ensure that increasing values of *Mgmt* reflect greater management appropriateness, and thus remains consistency with the other two RII components (*Site* and *Spec*), the normalized values were inverted (i.e., transformed as 1.00 - x), such that 1.00 represents the most appropriate management.

Therefore, if a fresh grassland site *i* was mown once and then grazed with 0.5 livestock units ha^{-1} ($Intensity_i = (1 \times 0.5) + 0.5 = 1$), the deviation of management appropriateness before min-max-scaling was $Deviation_i = (1–0.75)\ /\ 0.75 = 0.33$, indicating too intensive management comparable to 0.33 livestock units ha^{-1}. After standardization and inversion, $Mgmt_i = 1 - \left|\frac{(0.33-0.00)}{(1.43-0.00)}\right| = 0.77$.

2.2.4. Calculation of the Restoration Intensity Index

For each site *i* we defined the RII by summing up the values of the three components. Before addition, the *Site* and *Spec* components were standardized to values between 0.00 and 1.00 by using min-max standardization so that the values of all components were on the same scale, and each component had the same share of RII. Therefore, the RII could range between 0.00 and 3.00 in this study.

$$RII_i = Site_i + Spec_i + Mgmt_i$$

The RII can be applied either as a composite index or by analyzing its components separately, the latter enabling the consideration of synergistic or antagonistic interactions among them.

2.3. Vegetation parameters to assess restoration success

We chose vegetation parameters as indicators of restoration success. From vegetation survey data (Laschke et al., 2026), we derived four response variables, i.e., (i) overall plant species richness, (ii) target plant species richness, (iii) proportion of forb cover, and (iv) the Hill-Shannon diversity.

Target species were defined as those plants that are listed as characteristic for grasslands according to the EUNIS habitat classification (Chytrý et al., 2020) and the German reference list of the Habitats Directive (BfN and BLAK, 2017). As the latter does not cover all wet and moist grassland habitats, we included characteristic *Calthion* species listed in the biotope mapping guidelines of the federal states of Bavaria, Hamburg, Lower Saxony, Saxony-Anhalt, and Schleswig-Holstein (NLWKN, 2011; MULE, 2020; LfU Bayern, 2022; Brandt et al., 2023; LfU SH, 2023); woody species were excluded. The proportion of forb cover meant the percentage of legumes and other forbs in the total cumulative vegetation cover. Hill-Shannon diversity constituted the effective number of common or typical species in the plant community and integrated the no. of species as well as the evenness of species relative cover values (Chao et al., 2014).

The chosen vegetation parameters were selected because they are well-suited to characterise and assess the condition of grassland habitats, and represent important aspects for the wildlife they host. The aim of restoration is to facilitate and to maintain a high species diversity, with a focus on characteristic species (‘target species’). A high species richness increases resilience to environmental impacts (e.g., droughts;

Haughey et al., 2018). Forb-rich vegetation, especially in combination with a high effective species number (Hill-Shannon diversity), better promote higher trophic levels (e.g., source for pollen, nectar, seeds, and larvae host plants) (Schmidt et al., 2022a; Schmidt et al., 2022b; Schubert et al., 2022; Nerlekar et al., 2024). We used the relative proportion rather than the absolute cover of forbs for a more accurate comparison across different vegetation types, which vary considerably in sward densities (ca. 30–100%). Forbs are furthermore more sensitive to intensive or insufficient management and overfertilization, in which cases grasses may dominate (You et al., 2017; Dullau et al., 2023; Köhler et al., 2023). The dominance of few species, indicated by low Hill-Shannon diversity, can lead to species impoverishment over time, thus threatening restoration success in the long term.

2.4. Statistical analysis

A two-step modelling approach was used to analyze the relationship between the RII and restoration success. The first step evaluated whether the compounded RII is associated with four different indicators of restoration success, which are detailed below. In a second step, we assessed the associations of the three RII components, i.e., site preparation intensity (*Site*), species introduction quality (*Spec*), and management appropriateness (*Mgmt*), with the restoration success indicators, to better understand their relative importance for the overall RII effects as well as their potential synergistic or antagonistic interactions. The following four vegetation parameters were used as indicators of restoration success and response variables in both steps, i.e., (i) species richness, (ii) target species richness, (iii) Hill-Shannon diversity, and (iv) proportion forb cover. Multicollinearity was tested for all components and restoration age prior to the analyses (Fig. S1). Most correlations were low ($|r| < 0.15$), with the exception of *Site* and *Spec*, which showed a correlation of $r = 0.49$. However, this value remained below the commonly accepted threshold for moderate to strong correlation ($|r| > 0.7$; Dormann et al., 2013).

For the first step (quantifying the effect of the RII on the vegetation parameters), we considered the RII, region (north, central, south), soil moisture level (dry, fresh, moist), and restoration age (Table 3) as predictors. Restoration age (*Age*) refers to the period of years following the implementation of the main restoration intervention, or, in the case of management adaptation, to the time since the management adaptation started (2–30 years).

In a second step (disentangling contribution of the three RII components), we included the three RII components (region, soil moisture level, and restoration age (*Age*)) as predictors. To consider interactions between RII components as well as between RII components and restoration age, we fitted three models for each of the four response variables, i.e., (i) with main effects of the RII components, restoration age, region, and soil moisture; (ii) with all main effects as in (i), but with additional pairwise interactions of the three RII components; and (iii) with all main effects as in (i), but with additional pairwise interactions of each of the three RII components with restoration age (Table 4).

For response variables representing counts (overall and target species richness) we fitted generalized linear models (GLMs) with log-link function and negative binomial error distribution to account for overdispersion. For continuous response variables (proportion of forb cover, Hill-Shannon), we used linear models (LMs). We produced diagnostic plots to confirm that model assumptions were not violated. We applied Likelihood-Ratio-Tests to assess the associations of the predictor variables and their interactions, if applicable, with the response four variables. We provided R^2 values for all fitted models. For linear models, we reported the standard multiple R^2, while for GLMs we derived the Pseudo-R^2 as suggested by Nakagawa and Schielzeth (2013). We used the R software (version 4.4.1) (R Core Team, 2024) and the package MuMIn (Bartoń, 2024) for all statistical analyses.

3. Results

3.1. General patterns of the RII, components, and vegetation characteristics

On the 77 grassland sites, 485 plant species including 297 target species were recorded (Table S3). On average, 42.2 ± 15.0 species and 35.0 ± 13.3 target species were found on 16 m^2 per site (Table S4).

Vegetation parameters, the RII, and its components varied across regions and soil moisture levels (Tables 3–4, Tables S4–5, Fig. S2–4). Total and target plant species richness and Hill-Shannon diversity, the RII and all its components increased from North to South. Dry sites showed the highest overall and target plant species richness and Hill-Shannon diversity, followed by moist sites, and were lowest at fresh sites. The proportion of forb cover decreased from dry to moist sites. Across the 77 grassland sites, species introduction quality was high on 64.9% of the sites (*Spec* ≥ 0.5), while no species were introduced to 18 sites (Fig. S4 E − F). The seed mixtures used comprised 4–68 vascular plant species and 2.0–81.8% proportion of forb cover. Before the restoration intervention, site preparation, most commonly harrowing, was applied at 85.7% of the sites. Management appropriateness was rather high (*Mgmt* ≥ 0.8) on most sites; in total, 17 sites were grazed, 47 were mown, and ten were both grazed and mown.

The distributions of RII components were strongly right- (*Site*) or left-skewed (*Mgmt*). Only when all three components were combined as RII, the distribution was more symmetric and similar to a normal distribution (Fig. S5).

Table 3

Influence of the Restoration Intensity Index (RII), region (North, Centre, South), soil moisture level (dry, fresh, moist) and restoration age on grassland restoration success. The table summarizes four models with different response variables. For each model, an R^2 value and likelihood-ratio-tests for all explanatory variables are reported. For overall and target species richness generalized linear models (GLMs) were used, while linear models (LMs) were fitted to Hill-Shannon and proportion of forb cover. Pseudo-R^2 values for GLMs were estimated using the trigamma estimator provided in R package MuMIn (Bartoń, 2024).

Response variable	Explanatory variable	(Pseudo) R^2	LRT/F-value	Pr(>Chi)	Sig. code
Species richness (GLM)	RII	0.59	12.59	<0.001	***
	Region		39.28	<0.001	***
	Soil moisture		24.92	<0.001	***
Target species richness (GLM)	RII	0.61	12.11	<0.001	***
	Region		41.55	<0.001	***
	Soil moisture		28.57	<0.001	***
Hill-Shannon (LM)	RII	0.64	5.15	0.095	.
	Region		33.94	<0.001	***
	Soil moisture		6.14	0.005	**
Proportion forb cover [%] (LM)	RII	0.29	1.96	0.166	
	Region		2.44	0.094	.
	Soil moisture		9.85	<0.001	***

Table 4
Model results (GLMs and LMs) showing the effects of the components of the Restoration Intensity Index, i.e., site preparation (*Site*), species introduction (*Spec*), management (*Mgmt*), restoration age (*Age*), the regions (North, Centre, South), and soil moisture level (dry, fresh, moist) on the vegetation parameters overall and target plant species richness, Hill-Shannon diversity, and the proportion of forb cover. For each response, three models were tested including either the single components, interactions of the components or interactions of the component and restoration age. Region and soil hydrology were included in all models. Only the predictors that affect the vegetation parameters significantly were listed. The LRT, F- and p-values from the drop1 tables were selected. R^2 values were extracted from summary (LMs) and r.squared GLMM (GLMs) tables.

Response	Model (GLMs)	(Pseudo) R^2	Explanatory variable	LRT	Pr(>Chi)	Sig. code
Species richness	Mgmt + Spec + Site + Age	0.61	Species introduction	8.38	0.004	**
			Region	37.90	<0.001	***
			Soil moisture	24.31	<0.001	***
	(Mgmt + Spec + Site)^2 + Age	0.63	Region	31.03	<0.001	***
			Soil moisture	25.12	<0.001	***
	(Mgmt + Age)^2 + (Spec + Age)^2 + (Site + Age)^2	0.63	Region	31.64	<0.001	***
			Soil moisture	22.63	<0.001	***
Target species richness	Mgmt + Spec + Site + Age	0.63	Species introduction	10.02	0.002	**
			Region	38.42	<0.001	***
			Soil moisture	30.52	<0.001	***
	(Mgmt + Spec + Site)^2 + Age	0.62	Region	30.40	<0.001	***
			Soil moisture	26.73	<0.001	***
	(Mgmt + Age)^2 + (Spec + Age)^2 + (Site + Age)^2	0.64	Region	33.10	<0.001	***
			Soil moisture	28.13	<0.001	***

Response	Model (LMs)	Multiple R^2	Explanatory variable	F-value	Pr(>F)	Sig. code
Hill-Shannon	Mgmt + Spec + Site + Age	0.66	Region	32.37	<0.001	***
			Soil moisture	5.21	0.008	**
	(Mgmt + Spec + Site)^2 + Age	0.67	Region	27.49	<0.001	***
			Soil moisture	4.66	0.013	*
	(Mgmt + Age)^2 + (Spec + Age)^2 + (Site + Age)^2	0.67	Region	26.51	<0.001	***
			Soil moisture	4.06	0.022	*
Proportion forb cover [%]	Mgmt + Spec + Site + Age	0.31	Species introduction	3.92	0.052	.
			Region	3.33	0.042	*
			Soil moisture	8.08	<0.001	***
	(Mgmt + Spec + Site)^2 + Age	0.32	Region	3.03	0.055	.
			Soil moisture	7.87	<0.001	***
	(Mgmt + Age)^2 + (Spec + Age)^2 + (Site + Age)^2	0.42	Site preparation × restoration age	11.70	0.001	**
			Soil moisture	8.65	<0.001	***

3.2. Relation between Restoration Intensity Index (RII) and vegetation characteristics

An increasing RII was associated with increasing overall and target plant species richness and also the Hill-Shannon diversity tended to increase with RII (Table 3, Fig. 1). The proportion of forbs was not significantly associated with variation in the RII. The models including RII, region, and soil moisture explained a successful restoration, with an explanatory power of ca. 60% for all vegetation characteristics except for the proportion of forb cover (ca. 30%) (Table 3).

3.3. Contributions of the RII components to restoration

Looking at the individual components, species introduction quality was positively associated with overall and target species richness and also the proportion of forb cover tended to increase with increasing RII (Table 4, Fig. 2). By contrast, the response variables were not significantly associated with *Site* and *Mgmt* (Table 4, Fig. S6–7), which implies that the correlation between RII and the tested vegetation parameters were primarily driven by a high species introduction quality.

Across all models, we found no significant interaction effect of the RII components on the response variables, and only a significant interaction between *Age* and *Site* on forb cover (Fig. S8). When the RII components were analysed as separate variables, their joint explanatory power was comparable to that of the aggregated index.

4. Discussion

4.1. Application and adaptation of the Restoration Intensity Index

The aim of this paper was to develop and test a multi-dimensional Restoration Intensity Index (RII), which integrates the key components of grassland restoration, i.e., 'site preparation intensity', 'species introduction quality', and 'management appropriateness' (Tölgyesi et al., 2021; Slodowicz et al., 2023), into a continuous measure. The functioning of the RII was evaluated using restoration success, represented by vegetation characteristics, based on the assumption a high recovery is achieved by high levels of restoration intensity. The RII delivered consistent results, showing clear positive relationships between restoration intensity and various vegetation characteristics. Thus, the RII is a useful tool for estimating the effects of overall restoration intensity, as well as the contribution and effect of its key components for indicators of restoration success.

By quantifying complex restoration processes, the RII enables a systematic comparison across methods, studies, and regions, particularly in the context of research. It can be applied either as a single index or through analysis of its individual components, depending on the research objective. While a single index may enhance interpretability (e.g., for deriving evidence-based recommendations in policy contexts or cross-regional comparisons), aggregating components may mask the relative importance of individual components or potential interactions among them. Therefore, we recommend analyzing components separately, when the RII should be used as a diagnostic tool. Furthermore, the RII may have the potential to predict outcomes of planned restoration actions, thereby guiding site-specific interventions and management decisions. However, as this application has not been tested in this

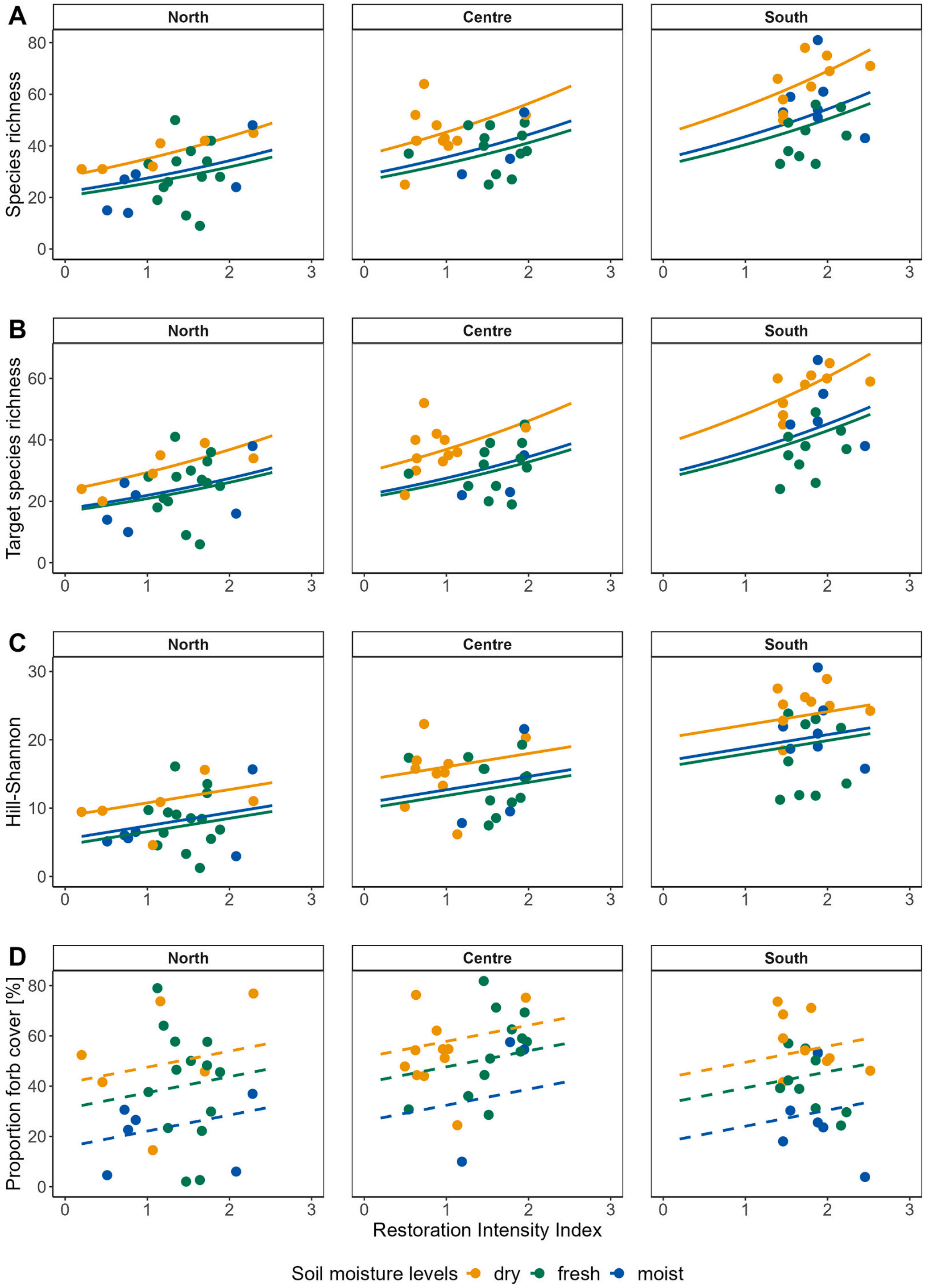

Fig. 1. Relationships between the overall and target plant species richness, proportion of forb cover, and Hill-Shannon index of grasslands and the Restoration Intensity Index (RII) in the three study regions and soil moisture levels. Hill-Shannon diversity denotes the effective number of species at a site if all species are distributed evenly. The lines represent the predicted significant or marginally significant model results ($p < 0.10$). Dashed lines indicate predicted non-significant results ($p > 0.10$).

study, it should be addressed in future research.

The RII was developed based on the framework of grassland restoration in Germany. However, the index can easily be adapted and applied to other grassland habitats and other types of restoration around the world by adding and adjusting the components with regard to relevant restoration methods (e.g., burning for the restoration of heathland habitats), commonly applied management practices (e.g., fertilization, *sensu* Blüthgen et al., 2012) or even extending the index by including further components (e.g., previous land-use). In order to achieve an equal weighting, it is only necessary to standardize the individual components between 0.00 and 1.00 before the aggregation or statistical evaluation. However, when restoring habitats where it is known that the components are of varying importance for ecosystem recovery, the individual components can also be weighted as required. When restoring a degraded peatland, for example, the creation of suitable hydrological conditions is crucial and the *Site* component can be

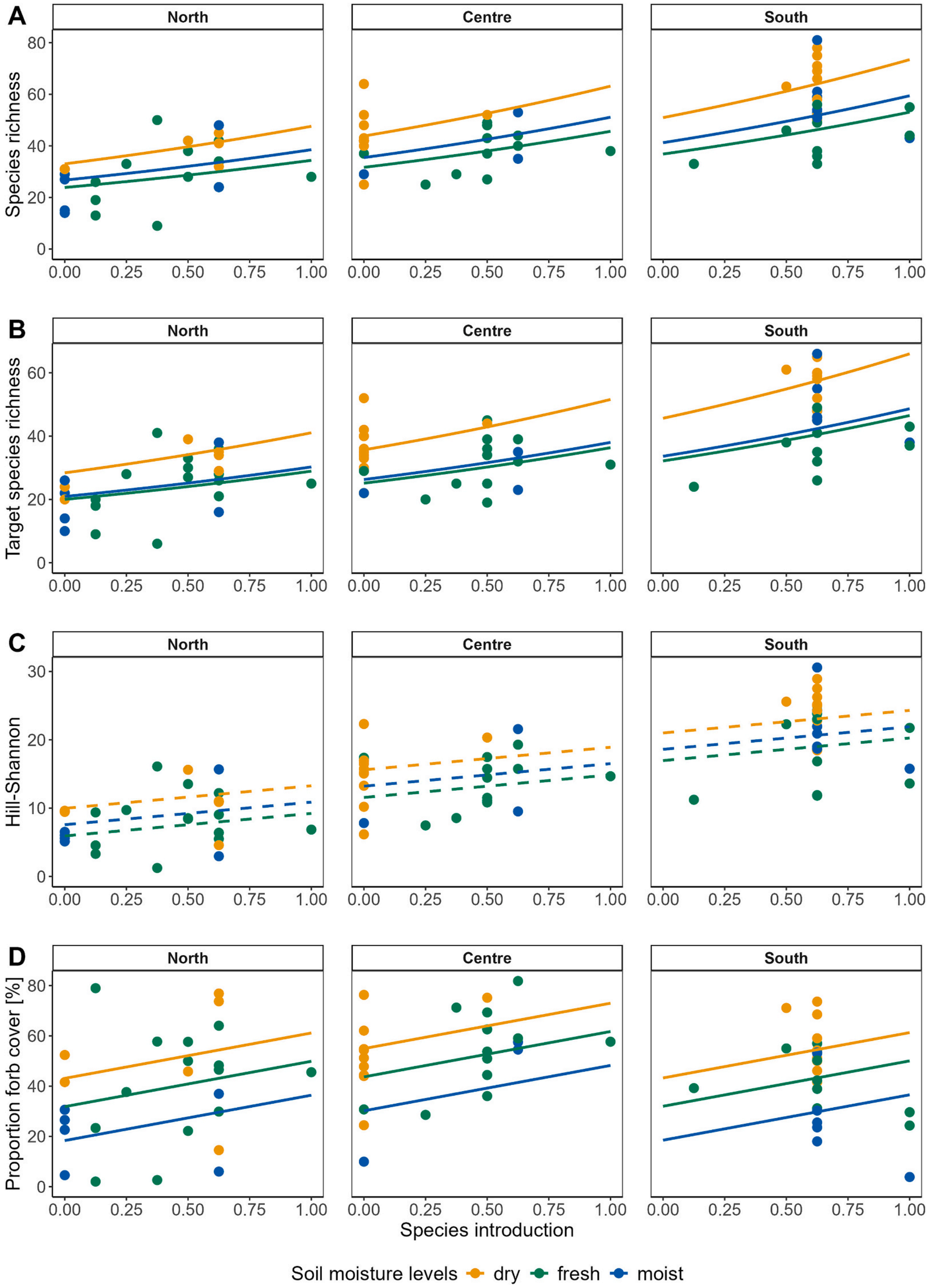

Fig. 2. Relationships between the overall and target plant species richness, proportion of forbs in total plant cover, and Hill-Shannon index of grasslands and the Restoration Intensity Index's component species introduction quality (*Spec*) in the three study regions and soil moisture levels. Hill-Shannon diversity denotes the effective number of species at a site if all species are distributed evenly. The lines represent the predicted significant and marginally significant model results ($p < 0.10$). To derive these model predictions, the other two RII components (site preparation and management) were fixed at their mean values. Dashed lines indicate predicted non-significant results ($p > 0.10$).

given higher weight in the RII calculation.

The study used vegetation characteristics as output variables, which is appropriate, because plant diversity is a key component for biodiversity of other taxa and broader ecosystem recovery. Successful restoration of vegetation initiates a higher structural diversity, a broader range of food supplies and nesting habitats, which in turn principally lead to the re-establishment of characteristic animal species and stabilization of food webs (Segre et al., 2023). However, in future studies, the RII could also be modified for multi-taxa assessments by adapting or adding components. Depending on the taxa involved, the *Mgmt* component should, for example, take into account the timing of management, as well as whether the site is managed all at once or in stages, or whether parts of it are left unused, which is beneficial for many animals (Révész et al., 2025). Given that animals are not usually introduced, proximity to donor populations/sites (habitat connectivity) and area size (minimum areal) should be considered as further components.

When comparisons across multiple regions or studies are intended, all data must be scaled jointly. To facilitate such purposes and to ease interpretation of results, future studies employing the RII should consistently report the absolute values, or at least absolute minimum and maximum values, for all components. In the present study, the RII is composed of three components, each assuming values from 0 to 1. Consequently, the RII ranges from 0 to 3. If additional components are incorporated, the overall range of the RII varies accordingly. To ensure comparability between studies with differing numbers of components, the RII of each study can also be scaled to the interval 0–1 by division with the potential RII maximum, which is equal to the number of components.

Irrespective of the habitat and investigated taxa, the calculation of the RII is based on conceptual considerations and knowledge of restoration practices that rank the individual measures to achieve a representation of intensity or quality for each component. Although the ranking and also the calculation of the index is conceptually advantageous, ecological knowledge and site-specific information on all components are necessary to maximize the potential of the index. Data collection can be challenging for sites that were restored a long time ago, especially when the involved people are no longer available. Thus, a database on restored grasslands with structured entries on measures, site locations and chronology of restoration interventions would be important for long-term evaluations of restoration measures and the optimisation of future restoration planning.

4.2. Evaluation of RII components

To increase the plant diversity and to overcome dispersal limitations ('dispersal filter'), the introduction of species is a commonly used method in grassland restoration (Kiehl et al., 2010; Shaw et al., 2020). For the species introduction component (*Spec*), we defined levels for ranking and weighting their quality based on the origin and propagation of the species included, the number of forb species and their proportion in the seed mixture. To better analyse the effect of species introduction quality, it would be desirable to use the absolute number of introduced species and the percentage of forbs in the applied seed containing material instead of ranked levels. Unfortunately, this was not possible because no data on the species richness or forb cover of donor sites were available for the direct harvesting methods. As the limited knowledge of transferred plant species for direct harvesting methods is often reported, we consider the ranking to be appropriate, taking into account scientific knowledge and practical constraints.

An appropriate and adapted management in grasslands is mandatory to stop further succession, to regulate interspecific competition ('biotic filter'), and to control vegetation development (Poschlod et al., 2009; Elias and Tischew, 2016; Nolan et al., 2021). In general, grasslands are mown, grazed, or both with variable intensity and different livestock, depending on several factors, such as productivity, terrain, accessibility, and availability of infrastructure. As the management intensity between meadows and pastures is difficult to compare, the LUI by Blüthgen et al. (2012) allows a comparison between the management types. The *Mgmt* component of the RII introduced here is similar to the LUI, but assesses the management appropriateness rather than its intensity. To determine management appropriateness, we compared the land-use intensity of the site in question to the land-use of well-managed species-rich permanent grasslands (positive references) for vegetation types of the same hydrology level. Blüthgen et al. (2012) suggested calculating the intensity in relation to regional grassland use. However, this does not take into account the productivity of the site or the amount of biomass that can be removed to achieve or maintain the desired vegetation. We further decided against using static management recommendations from literature, since site-specific management is a key factor for the persistence of target plant species in restored grasslands (Lyons et al., 2023). In the study sites, we found that some fresh grasslands were only mown once a year instead of twice as commonly recommended for this grassland type (e.g., Dullau and Tischew, 2019), since the below-average precipitation levels in 2022 resulted in low biomass yields. Therefore, the year chosen as reference for the index can have a significant impact on the results (Blüthgen et al., 2012). In addition, the effect of management on vegetation is rather slow, and thus, changes can only be seen after several years (Tölgyesi et al., 2021). Due to data limitations, we included the management of only one year in the *Mgmt* component. If data are available, the variability of vegetation parameters and management should be illustrated by providing multi-year average data when calculating the *Mgmt* component (Blüthgen et al., 2012).

The site preparation component describes the extent to which the former vegetation and soil were altered, e.g., to reduce competition from the existing vegetation ('abiotic' and 'biotic' filters). The removal of the previous vegetation and thus intense soil and seed bed preparation were also identified in former studies as an important prerequisite for the establishment of the target plant community (e.g., Schmiede et al., 2012). Nutrient removal (arable farming without fertilization) and raising the groundwater level were treated as abiotic measures with a medium (0.5) rank. These measures can be carried out in addition to soil preparation measures, but were scarce in the GRASSWORKS dataset. For example, raising the groundwater level might be more common as a measure in datasets containing also wet grasslands on peat soils. In fact, the intensity of site preparation needed depends on land-use history, and the site condition just before species introduction. As an extreme example, a 10-year fallow might require shrub removal, mulching, and ploughing to establish a suitable seed bed, while similar conditions can be achieved on an arable land by grubbing only. Even within arable land, the extent of weed infestation on the site can be decisive. In the GRASSWORKS dataset, the site preparation measures were specified by the respondents in the questionnaires, thus the specification between previous land use and site preparation was made implicitly. We recommend that further studies define the differentiation between former land use and site preparation more explicitly and integrate the initial state of the site into the RII.

4.3. Influence of RII, its components and restoration age on grassland quality

Evaluation of RII using the GRASSWORKS dataset showed a high explanatory power for the studied indicators of restoration success. These findings validate the index and indicate that intensified restoration efforts effectively mitigate environmental filters, facilitating grassland recovery. This aligns with McFarlane et al. (2023), who demonstrated positive effects of restoration intensity on prairie vegetation indicators, assessed via a four-level categorical scale. Conversely, Jones et al. (2018) reported in a global meta-analysis that active restoration (i.e., seed addition to overcome dispersal limitation) does not consistently outperform passive restoration across diverse ecosystems. Notably, neither study quantified restoration intensity per se.

Within the test data set, we identified the quality of species introduction (*Spec*), as the component with the strongest influence on our indicators of grassland restoration success. *Spec* was correlated with the overall and target plant species richness and the proportion of forb cover. This suggests that the active introduction of species- and forb-rich regional seed mixtures or directly harvested material are a key driver for successful restoration and is of utmost importance for future restoration. Furthermore, all sites restored at a low species introduction quality, using cultivar seed mixes, had low vegetation quality and diversity. This is consistent with other studies that found that restoration success depends on species richness of the seed mixture (Kirmer et al., 2012; Freitag et al., 2021), while direct harvesting is also successful (Valkó et al., 2022). In contrast to overall and target species richness, high-quality species introduction did not increase Hill-Shannon diversity, in contrast to a high restoration intensity (based on the RII). This indicates that the *Spec* component strongly drives the presence but less the cover of rare species, whereas a high overall restoration intensity promotes both. However, sites without species introduction sometimes had higher values for the vegetation parameters tested. Most of these sites were grasslands whose management was adapted with the aim of optimizing them for nature conservation within a protected area. According to Jones et al. (2018) and Dellicour et al. (2023), active restoration does not consistently result in faster or more complete ecosystem recovery compared to passive restoration, as those responsible for restoration may correctly choose which sites can or cannot recover on their own (e.g. Prach et al., 2021). Thus, sites where species have been introduced may have lower species richness before restoration than sites where no species have been introduced, but this may lead to a similar outcome, especially in more species-rich grazed landscapes (Tölgyesi et al., 2021).

Compared to the *Spec* component, management appropriateness (*Mgmt*) was of minor importance with regard to restoration success and showed no significant effects on variables when all RII components were included. This contradicts studies that have emphasized the importance of an appropriate management for maintaining long-term species richness in grassland (Öckinger et al., 2006; Tölgyesi et al., 2021). This discrepancy may be due to the fact that other studies tested management as a binary factor (with or without the management) at the same site with otherwise identical treatments, whereas our approach is more complex and shows that optimal management alone does not lead to restoration success. Another explanation for the low effect of *Mgmt* could be that most of our study sites were well-managed, resulting in a weak gradient of management intensity. Most sites were restored as impact mitigation, agri-environmental schemes, contract-based, or project-based nature conservation. Their follow-up management after restoration intervention is subject to restrictions from agri-environmental schemes, maintenance contracts or contract-based conservation. This is also reflected by the fact that only two positive reference sites were fertilized at a very low level, while fertilization is a standard practice in non-conservation grassland management (Dullau et al., 2023). A further issue could be the component's potential insensitivity, given that we used data from one year only. Furthermore, we were not able to account for the timing of management, which is crucial for e.g., regulating the proportion of forbs, as a late first management promotes grass cover (Kirmer et al., 2018).

The RII component site preparation intensity (*Site*) alone led to no considerable increase of any vegetation characteristics. This is in contrast to the findings of other studies (e.g., Kiehl et al., 2010; Freitag et al., 2021) which recommended the creation of open soil by removing or weakening existing swards before species introduction to facilitate the establishment of the target community. The lack of significance in this study may be due to the fact that 85% of our sites had previously been harrowed at least once. This may have resulted in a relatively narrow *Site* gradient in contrast to large variation in *Spec*. However, the differences in restoration outcome of the eleven sites with species introduction but without any site preparation is likely due to land-use history (sensu Donath et al., 2007), as some sites were former arable land and some were grasslands. If a site has been intensively farmed with, e.g., herbicide application for a long time prior to restoration, resulting in an impoverished seed bank and bare soil, intensive site preparation is not necessary.

According to Buisson et al. (2022) secondary grasslands may typically require at least a century to fully recover. As restoration age typically increases species richness (Prach et al., 2013; Dellicour et al., 2023), we hypothesized increasing importance of *Mgmt* and decreasing effects of *Site* and *Spec* over time. This was only partially confirmed: intensive site preparation increased forb cover at young (<15 yr) sites but reversed at older sites, especially in fresh grasslands. However, our results may be biased by the uneven distribution of applied intervention methods over time (Fig. S9), as a high percentage of the oldest study sites were restored by using species-poor cultivar seed mixtures containing up to 98% grass seeds in total seed weight. These commercially available seed mixtures were best practice in the past, but are no longer applied for nature conservation due to knowledge gain and restrictions by the German legislation. In general, our results are in line with other studies, which found a decline in vegetation quality with increasing restoration age (Török et al., 2011; McFarlane et al., 2023). In addition, over time some species may outcompete others (McFarlane et al., 2023). In the case of introduced species, this could be due to inappropriate management or the fact that the abiotic site conditions were not optimal. In sites restored by management adaptation, species that are not typical for the habitat (ecotone species, ruderal species) may disappear over time. Therefore, we conclude that the lack of change in importance of the components with age again indicates that appropriate management alone is insufficient if the species are no longer present on the site or in its immediate vicinity.

Finally, species richness-related vegetation characteristics varied significantly across soil moisture levels and regions. This was to be expected, as the grasslands included are known to exhibit a gradient, ranging from semi-dry to moist sites (Leuschner and Ellenberg, 2017). The same applies for the region along a south-north gradient with the flora of southern Germany being more species-rich. However, the integration of these gradients in the validation process enhanced the predictive capability of the RII. In our analyses of the proportion of forb cover, the coefficients of determination (R^2) showed weaker results, indicating other unknown factors that were not considered. For example, the surrounding landscape could affect vegetation development on the restored sites, as it is known that in homogenized, isolated, or fragmented landscapes a lack of diaspores of characteristic target species and/or suitable dispersal vectors are a limiting factor for grassland restoration success (Funk et al., 2008; Öster et al., 2009b; Kiehl et al., 2010).

5. Conclusions

The proposed RII is effective in integrating and assessing the main components of grassland restoration. The index is flexible and might be adapted to restoration of different grassland types as well as other ecosystems, taxa and other regions. Future research should evaluate the extent to which the RII predicts biodiversity for plants, animal taxa (e.g., insects), ecosystem functions, socio-economic indicators, as well as multifunctionality. Further studies should test the applicability of the RII to other datasets. The RII showed a clear positive relationship between overall restoration intensity and desired vegetation restoration outcomes, as one of the key components of restoration success. This points out that increased efforts in restoration intervention lead to greater ecological restoration success and therefore grassland recovery. However, increasing species introduction quality and thus applying regional seeds with a high forb richness and a high proportion of forb seeds were identified as key drivers for successful grassland restoration.

CRediT authorship contribution statement

Annika Schmidt: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Felix May:** Writing – review & editing, Methodology. **Regina Neudert:** Writing – review & editing, Investigation, Data curation. **Anita Kirmer:** Writing – review & editing, Funding acquisition. **Johannes Kollmann:** Writing – review & editing, Funding acquisition. **Vicky M. Temperton:** Writing – review & editing, Funding acquisition. **Christin Juno Laschke:** Writing – review & editing, Investigation. **Line Sturm:** Writing – review & editing, Investigation. **Miriam Wiesmeier:** Writing – review & editing, Investigation. **Alina Twerski:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

No AI-assisted technologies or services have been used during the preparation of this work.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2026.114912.

Data availability

Data will be made available on request.

References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von, Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W., Lang, D.J., 2017. Leverage points for sustainability transformation. Ambio 46 (1), 30–39.

Bartoń, K., 2024. MuMIn: Multi-Model Inference. R package version 1.48.4.

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H.G., Lindborg, R., 2019. Grasslands—more important for ecosystem services than you might think. Ecosphere 10 (2).

BfN, BLAK, 2017. Bewertungsschemata für die Bewertung des Erhaltungsgrades von Arten und Lebensraumtypen als Grundlage für ein bundesweites FFH-Monitoring : Teil II: Lebensraumtypen nach Anhang I der FFH-Richtlinie (mit Ausnahme der marinen und Küstenlebensräume), 481st ed. Bundesamt für Naturschutz, Bonn (de).

Blüthgen, N., Dormann, C.F., Prati, D., Klaus, V.H., Kleinebecker, T., Hölzel, N., Alt, F., Boch, S., Gockel, S., Hemp, A., Müller, J., Nieschulze, J., Renner, S.C., Schöning, I., Schumacher, U., Socher, S.A., Wells, K., Birkhofer, K., Buscot, F., Oelmann, Y., Rothenwöhrer, C., Scherber, C., Tscharntke, T., Weiner, C.N., Fischer, M., Kalko, E. K., Linsenmair, K.E., Schulze, E.-D., Weisser, W.W., 2012. A quantitative index of land-use intensity in grasslands: integrating mowing, grazing and fertilization. Basic Appl. Ecol. 13 (3), 207–220.

Brandt, I., Hastedt, J., Haacks, M., 2023. Kartieranleitung und Biotoptypenschlüssel für die Biotopkartierung in Hamburg: einschließlich der Definitionen besonders geschützter Biotope nach §. Freie und Hansestadt Hamburg, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft.

Brudvig, L.A., Catano, C.P., 2024. Prediction and uncertainty in restoration science. Restor. Ecol. 32 (8).

Brudvig, L.A., Barak, R.S., Bauer, J.T., Caughlin, T.T., Laughlin, D.C., Larios, L., Matthews, J.W., Stuble, K.L., Turley, N.E., Zirbel, C.R., 2017. Interpreting variation to advance predictive restoration science. J. Appl. Ecol. 54 (4), 1018–1027.

Bucharova, A., Bossdorf, O., Hölzel, N., Kollmann, J., Prasse, R., Durka, W., 2019. Mix and match: regional admixture provenancing strikes a balance among different seed-sourcing strategies for ecological restoration. Conserv. Genet. 20 (1), 7–17.

Buisson, E., Archibald, S., Fidelis, A., Suding, K.N., 2022. Ancient grasslands guide ambitious goals in grassland restoration. Science (New York, N.Y.) 377 (6606), 594–598.

Buttler, K.P., Thieme, M., 2018. Florenliste von Deutschland - Gefäßpflanzen. Version 10 (August 2018). Archivierte Fassung als PDF-Datei.

Chao, A., Chiu, C.-H., Jost, L., 2014. Unifying species diversity, phylogenetic diversity, functional diversity, and related similarity and differentiation measures through hill numbers. Annu. Rev. Ecol. Evol. Syst. 45 (1), 297–324.

Chazdon, R.L., Falk, D.A., Banin, L.F., Wagner, M., J. Wilson, S., Grabowski, R.C., Suding, K.N., 2024. The intervention continuum in restoration ecology: rethinking the active–passive dichotomy. Restor. Ecol. 32 (8).

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., Attorre, F., Bergmeier, E., Biurrun, I., Boch, S., Bölöni, J., Bonari, G., Braslavskaya, T., Bruelheide, H., Campos, J.A., Čarni, A., Casella, L., Ćuk, M., Ćušterevska, R., de E., Bie, Delbosc, P., Demina, O., Didukh, Y.P., Dítě, D., Dziuba, T., Ewald, J., Gavilán, R.G., Gégout, J.-C., Del Giusso Galdo, G.P., Golub, V., Goncharova, N., Goral, F., Graf, U., Indreica, A., Isermann, M., Jandt, U., Jansen, F., Jansen, J., Jašková, A., Jiroušek, M., Kącki, Z., Kalníková, V., Kavgacı, A., Khanina, L., Korolyuk A., Yu., Kozhevnikova, M., Kuzemko, A., Küzmič, F., Kuznetsov, O.L., Laiviņš, M., Lavrinenko, I., Lavrinenko, O., Lebedeva, M., Lososová, Z., Lysenko, T., Maciejewski, L., Mardari, C., Marinšek, A., Napreenko, M. G., Onyshchenko, V., Pérez-Haase, A., Pielech, R., Prokhorov, V., Rašomavičius, V., Rodríguez-Rojo, M.P., Rūsiņa, S., Schrautzer, J., Šibík, J., Šilc, U., Škvorc, Ž., Smagin, V.A., Stančić, Z., Stanisci, A., Tikhonova, E., Tonteri, T., Uogintas, D., Valachovič, M., Vassilev, K., Vynokurov, D., Willner, W., Yamalov, S., Evans, D., Palitzsch Lund, M., Spyropoulou, R., Tryfon, E., Schaminée, J.H.J., 2020. EUNIS habitat classification: expert system, characteristic species combinations and distribution maps of european habitats. Appl. Veg. Sci. 23, 648–675.

Conrad, M.K., Tischew, S., 2011. Grassland restoration in practice: do we achieve the targets? A case study from Saxony-Anhalt/Germany. Ecol. Eng. 37 (8), 1149–1157.

Dellicour, M., Goret, T., Piqueray, J., Fayolle, A., Bindelle, J., Mahy, G., 2023. Success of passive and active restoration of lowland hay meadows with regard to current and historical references. Front. Ecol. Evol. 11.

Dengler, J., Tischew, S., 2018. Grasslands of western and northern europe – between intensification and abandonment. In: Grasslands of the world : diversity, management and conservation (9781498796262).

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

Diekmann, M., Andres, C., Becker, T., Bennie, J., Blüml, V., Bullock, J.M., Culmsee, H., Fanigliulo, M., Hahn, A., Heinken, T., Leuschner, C., Luka, S., Meißner, J., Müller, J., Newton, A., Peppler-Lisbach, C., Rosenthal, G., van den Berg, L.J.L., Vergeer, P., Wesche, K., 2019. Patterns of long-term vegetation change vary between different types of semi-natural grasslands in western and central Europe. J. Veg. Sci. 30 (2), 187–202.

Donath, T.W., Bissels, S., Hölzel, N., Otte, A., 2007. Large scale application of diaspore transfer with plant material in restoration practice – impact of seed and microsite limitation. Biol. Conserv. 138 (1–2), 224–234.

Dullau, S., Tischew, S., 2019. Gründlandleitfaden : Bewirtschaftungsempfehlungen für die Lebensraumtypen 6440, 6510 und 6520 in Sachsen-Anhalt (ger).

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36 (1), 27–46.

Dullau, S., Kirmer, A., Tischew, S., Holz, F., Meyer, M.H., 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. Glob. Ecol. Conserv. 48, e02730.

Durbecq, A., Jaunatre, R., Buisson, E., Favale, C., Maudieu, N., Bischoff, A., 2023. Persisting effects of seed bed preparation and early grazing on plant communities in grassland restoration. Front. Ecol. Evol. 11.

Elias, D., Tischew, S., 2016. Goat pasturing—a biological solution to counteract shrub encroachment on abandoned dry grasslands in central Europe? Agric. Ecosyst. Environ. 234, 98–106.

Fischer, M., Bossdorf, O., Gockel, S., Hänsel, F., Hemp, A., Hessenmöller, D., Korte, G., Nieschulze, J., Pfeiffer, S., Prati, D., Renner, S., Schöning, I., Schumacher, U., Wells, K., Buscot, F., Kalko, E.K., Linsenmair, K.E., Schulze, E.-D., Weisser, W.W., 2010. Implementing large-scale and long-term functional biodiversity research: the biodiversity exploratories. Basic Appl. Ecol. 11 (6), 473–485.

Freitag, M., Klaus, V.H., Bolliger, R., Hamer, U., Kleinebecker, T., Prati, D., Schäfer, D., Hölzel, N., 2021. Restoration of plant diversity in permanent grassland by seeding: assessing the limiting factors along land-use gradients. J. Appl. Ecol. 58 (8), 1681–1692.

Funk, J.L., 2021. Revising the trait-based filtering framework to include interacting filters: lessons from grassland restoration. J. Ecol. 109 (10), 3466–3472.

Funk, J.L., Cleland, E.E., Suding, K.N., Zavaleta, E.S., 2008. Restoration through reassembly: plant traits and invasion resistance. Trends Ecol. Evol. 23 (12), 695–703.

Garrouj, M., Alard, D., Dudit, J., Benot, M.-L., 2024. Transfer seeds, hay, or soil blocks? The importance of the completeness of biological inputs to address dispersal and establishment limitations during the restoration of plant assemblages in floodplain grasslands. Restor. Ecol. 32 (3).

Habel, J.C., Dengler, J., Janišová, M., Török, P., Wellstein, C., Wiezik, M., 2013. European grassland ecosystems: threatened hotspots of biodiversity. Biodivers. Conserv. 22 (10), 2131–2138.

Haughey, E., Suter, M., Hofer, D., Hoekstra, N.J., McElwain, J.C., Lüscher, A., Finn, J.A., 2018. Higher species richness enhances yield stability in intensively managed grasslands with experimental disturbance. Sci. Rep. 8 (1), 15047.

Jandt, U., Bruelheide, H., Jansen, F., Bonn, A., Grescho, V., Klenke, R.A., Sabatini, F.M., Bernhardt-Römermann, M., Blüml, V., Dengler, J., Diekmann, M., Doerfler, I., Döring, U., Dullinger, S., Haider, S., Heinken, T., Horchler, P., Kuhn, G., Lindner, M., Metze, K., Müller, N., Naaf, T., Peppler-Lisbach, C., Poschlod, P., Roscher, C., Rosenthal, G., Rumpf, S.B., Schmidt, W., Schrautzer, J., Schwabe, A., Schwartze, P., Sperle, T., Stanik, N., Storm, C., Voigt, W., Wegener, U., Wesche, K., Wittig, B., Wulf, M., 2022. More losses than gains during one century of plant biodiversity change in Germany. Nature 611 (7936), 512–518.

Jones, H.P., Jones, P.C., Barbier, E.B., Blackburn, R.C., Rey Benayas, J.M., Holl, K.D., McCrackin, M., Meli, P., Montoya, D., Mateos, D.M., 2018. Restoration and repair of earth's damaged ecosystems. Proc. Biol. Sci. 285 (1873).

Kardol, P., van der Wal, A., Bezemer, T.M., de W., Boer, Duyts, H., Holtkamp, R., van der Putten, W.H., 2008. Restoration of species-rich grasslands on ex-arable land: seed addition outweighs soil fertility reduction. Biol. Conserv. 141 (9), 2208–2217.

Kiehl, K., 2010. Plant species introduction in ecological restoration: possibilities and limitations. Basic Appl. Ecol. 11 (4), 281–284.

Kiehl, K., Kirmer, A., Donath, T.W., Rasran, L., Hölzel, N., 2010. Species introduction in restoration projects – evaluation of different techniques for the establishment of semi-natural grasslands in central and northwestern Europe. Basic Appl. Ecol. 11 (4), 285–299.

Kirmer, A., Tischew, S., 2006. Handbuch naturnahe Begrünung von Rohböden. Teubner, Wiesbaden.

Kirmer, A., Baasch, A., Tischew, S., 2012. Sowing of low and high diversity seed mixtures in ecological restoration of surface mined-land. Appl. Veg. Sci. 15 (2), 198–207.

Kirmer, A., Rydgren, K., Tischew, S., 2018. Smart management is key for successful diversification of field margins in highly productive farmland. Agric. Ecosyst. Environ. 251, 88–98.

Klaus, V.H., Schäfer, D., Kleinbecker, T., Fischer, M., Prati, D., Hölzel, N., 2016. Enriching plant diversity in grasslands by large-scale experimenteal sward disturbance and seed addition along gradients of land-use-intensity. JPECOL 169, 112846, 10(4).

Klaus, V.H., Richter, F.J., Buchmann, N., Hartmann, M., Lüscher, A., Huguenin-Elie, O., 2024. Indicators for assessing the multifunctionality of agriculturally used grasslands. Ecol. Indic. 169, 112846.

Köhler, M., Schmidt, A., Hölzel, N., Baasch, A., Tischew, S., 2023. Positive long-term effects of year-round horse grazing in orchid-rich dry calcareous grasslands–results of a 12-year study. Front. Ecol. Evol. 11.

Krickl, P., 2022. The Significance of Connectivity by Livestock for Restoration and Conservation of Calcareous Grasslands.

Lange, M., Eisenhauer, N., Chen, H., Gleixner, G., 2023. Increased soil carbon storage through plant diversity strengthens with time and extends into the subsoil. Glob. Chang. Biol. 29 (9), 2627–2639.

Laschke, C.J., Twerski, A., Bauer, M., Härdtle, W., Kirmer, A., Kollmann, J., Loos, J., Schmidt, A., Sturm, L., Tischew, S., Wiesmeier, M., Temerton, V.M., 2026. Integrated assessment of grassland restoration methods across Germany: direct harvest and regional seed mixtures are most successful for vegetation outcomes. J. Appl. Ecol. 63, e70390.

Leuschner, C., Ellenberg, H., 2017. Ecology of Central European Non-Forest Vegetation: Coastal to Alpine, Natural to Man-Made Habitats. Springer International Publishing, Cham.

LfU Bayern, 2022. Kartieranleitung biotopkartierung bayern (inkl. kartierung der Offenland-Lebensraumtypen der Fauna-Flora-Habitat-Richtlinie) - teil 2 - biotoptypen.

LfU SH, 2023. Kartieranleitung und erläuterte Standardliste der Biotoptypen Schleswig-Holsteins.- Version 2.2, Stand 04/23, 228.

Lyons, K.G., Török, P., Hermann, J.-M., Kiehl, K., Kirmer, A., Kollmann, J., Overbeck, G. E., Tischew, S., Allen, E.B., Bakker, J.D., Brigham, C., Buisson, E., Crawford, K., Dunwiddie, P., Firn, J., Grobert, D., Hickman, K., Le Stradic, S., Temperton, V.M., 2023. Challenges and opportunities for grassland restoration: a global perspective of best practices in the era of climate change. Glob. Ecol. Conserv. 46, e02612.

McFarlane, S.L., Kochanski, J.M., Gratton, C., Damschen, E.I., 2023. Intervention intensity predicts the quality and duration of prairie restoration outcomes. Restor. Ecol. 31 (8).

MULE, 2020. Biotoptypenrichtlinie des Landes Sachsen-Anhalt. RdErl. des MULE vom 15.2. 2020 - 24.2-2247. - veröffentlicht in: MBI. LSA Nr. 19/2020 vom 2.6.2020.

Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining r2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4 (2), 133–142.

Nerlekar, A.N., Sullivan, L.L., Brudvig, L.A., 2024. Grassland restorations must better foster forbs to facilitate high biodiversity. Restor. Ecol. 32 (7).

NLWKN, 2011. Artenreiches Nass- und Feuchtgrünland (außer Pfeifengras- und Brenndoldenwiesen). In: NLWKN (Ed.), Vollzugshinweise zum Schutz der FFH-Lebensraumtypen sowie weiterer Biotoptypen mit landesweiter Bedeutung in Niedersachsen. – Biotoptypen mit Priorität für Erhaltungs- und Entwicklungsmaßnahmen. NLWKN, Hannover, p. 15.

Nolan, M., Dewees, S., Ma Lucero, S., 2021. Identifying effective restoration approaches to maximize plant establishment in California grasslands through a meta-analysis. Restor. Ecol. 29 (4).

Öckinger, E., Eriksson, A.K., Smith, H.G., 2006. Effects of grassland abandonment, restoration and management on butterflies and vascular plants. Biol. Conserv. 133 (3), 291–300.

Öster, M., Ask, K., Cousins, S.A.O., Eriksson, O., 2009a. Dispersal and establishment limitation reduces the potential for successful restoration of semi-natural grassland communities on former arable fields. J. Appl. Ecol. 46 (6), 1266–1274.

Öster, M., Ask, K., Römermann, C., Tackenberg, O., Eriksson, O., 2009b. Plant colonization of ex-arable fields from adjacent species-rich grasslands: the importance of dispersal vs. recruitment ability. Agric. Ecosyst. Environ. 130 (3–4), 93–99.

Pazúr, R., Nováček, J., Bürgi, M., Kopecká, M., Lieskovský, J., Pazúrová, Z., Feranec, J., 2024. Changes in grassland cover in Europe from 1990 to 2018: trajectories and spatial patterns. Reg. Environ. Chang. 24 (2).

Petermann, J.S., Buzhdygan, O.Y., 2021. Grassland biodiversity. Curr. Biol. CB 31 (19), R1195–R1201.

Poschlod, P., Baumann, A., Karlik, P., 2009. Origin and development of grasslands in Central Europe. In: Veen, P., Jefferson, R., Smidt, J. de, van der Straaten, J. (Eds.), Grasslands in Europe. KNNV Publishing, pp. 15–25.

Prach, K., Jongepierová, I., Řehounková, K., 2013. Large-scale restoration of dry grasslands on ex-arable land using a regional seed mixture: establishment of target species. Restor. Ecol. 21 (1), 33–39.

Prach, K., Jongepierová, I., Řehounková, K., Fajmon, K., 2014. Restoration of grasslands on ex-arable land using regional and commercial seed mixtures and spontaneous succession: successional trajectories and changes in species richness. Agric. Ecosyst. Environ. 182, 131–136.

Prach, K., Fajmon, K., Řehounková, K., Jongepierová, I., 2021. Hierarchy of environmental factors driving restoration of dry grasslands: a multi-site analysis. Appl. Veg. Sci. 24 (2).

R Core Team, 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. www.R-project.org.

Resch, M.C., Schütz, M., Buchmann, N., Frey, B., Graf, U., van der Putten, W.H., Zimmermann, S., Risch, A.C., 2021. Evaluating long-term success in grassland restoration: an ecosystem multifunctionality approach. Ecol. Appl. 31 (3), e02271.

Révész, K., Gallé, R., Humbert, J.-Y., Batáry, P., 2025. Effects of uncut refuge management on grassland arthropods – a systematic review. Glob. Ecol. Conserv. 57, e03381.

Rosenthal, G., Hölzel, N., 2009. Renaturierung von Feuchtgrünland, Auengrünland und mesophilem Grünland. In: Zerbe, S., Wiegleb, G. (Eds.), Renaturierung von Ökosystemen in Mitteleuropa. Spektrum, Heidelberg, pp. 283–316.

Schils, R.L., Bufe, C., Rhymer, C.M., Francksen, R.M., Klaus, V.H., Abdalla, M., Milazzo, F., Lellei-Kovács, E., ten H., Berge, Bertora, C., Chodkiewicz, A., Dămătîrcă, C., Feigenwinter, I., Fernández-Rebollo, P., Ghiasi, S., Hejduk, S., Hiron, M., Janicka, M., Pellaton, R., Smith, K.E., Thorman, R., Vanwalleghem, T., Williams, J., Zavattaro, L., Kampen, J., Derkx, R., Smith, P., Whittingham, M.J., Buchmann, N., Price, J.P.N., 2022. Permanent grasslands in europe: land use change and intensification decrease their multifunctionality. Agric. Ecosyst. Environ. 330, 107891.

Schmidt, A., Kirmer, A., Kiehl, K., Tischew, S., 2020. Seed mixture strongly affects species-richness and quality of perennial flower strips on fertile soil. Basic Appl. Ecol. 42, 62–72.

Schmidt, A., Fartmann, T., Kiehl, K., Kirmer, A., Tischew, S., 2022a. Effects of perennial wildflower strips and landscape structure on birds in intensively farmed agricultural landscapes. Basic Appl. Ecol. 58, 15–25.

Schmidt, A., Kirmer, A., Hellwig, N., Kiehl, K., Tischew, S., 2022b. Evaluating CAP wildflower strips: high-quality seed mixtures significantly improve plant diversity and related pollen and nectar resources. J. Appl. Ecol. 59 (3), 860–871.

Schmiede, R., Otte, A., Donath, T.W., 2012. Enhancing plant biodiversity in species-poor grassland through plant material transfer – the impact of sward disturbance. Appl. Veg. Sci. 15 (2), 290–298.

Schnoor, T., Bruun, H.H., Olsson, P.A., 2015. Soil disturbance as a grassland restoration measure - effects on plant species composition and functional traits. PLoS One 10 (4).

Schubert, L.F., Hellwig, N., Kirmer, A., Schmid-Egger, C., Schmidt, A., Dieker, P., Tischew, S., 2022. Habitat quality and surrounding landscape structures influence wild bee occurrence in perennial wildflower strips. Basic Appl. Ecol. 60, 76–86.

Segre, H., Kleijn, D., Bartomeus, I., WallisDeVries, M.F., de M., Jong, van der Frank Schee, M., Román, J., Fijen, T.P., 2023. Butterflies are not a robust bioindicator for assessing pollinator communities, but floral resources offer a promising way forward. Ecol. Indic. 154, 110842.

Sengl, P., Magnes, M., Weitenthaler, K., Wagner, V., Erdős, L., Berg, C., 2017. Restoration of lowland meadows in Austria: a comparison of five techniques. Basic Appl. Ecol. 24, 19–29.

Shaw, N., Barak, R.S., Campbell, R.E., Kirmer, A., Pedrini, S., Dixon, K., Frischie, S., 2020. Seed use in the field: delivering seeds for restoration success. Restor. Ecol. 28 (S3).

Slodowicz, D., Durbecq, A., Ladouceur, E., Eschen, R., Humbert, J.-Y., Arlettaz, R., 2023. The relative effectiveness of different grassland restoration methods: a systematic literature search and meta-analysis. Ecol Sol Evid. 4 (2).

Sommer, L., Klinger, Y.P., Donath, T.W., Kleinebecker, T., Harvolk-Schöning, S., 2023. Long-term success of floodplain meadow restoration on species-poor grassland. Front. Ecol. Evol. 10, 1061484.

Staude, I.R., Segar, J., Temperton, V.M., Andrade, B.O., Sá Dechoum, M. de, Weidlich, E. W.A., Overbeck, G.E., 2023. Prioritize grassland restoration to bend the curve of biodiversity loss. Restor. Ecol. 31 (5).

Temperton, V.M., Hobbs, R.J., Nuttle, T., Halle, S., 2013. Assembly Rules and Restoration Ecology. Bridging the Gap Between Theory and Practice. Island Press (en).

Temperton, V.M., Pătru-Duşe, I.A., Twerski, A., Laeseke, P., Neudert, R., Cebrián-Piqueras, M.A., Romero, M.P., Bauer, M., Beckmann, V., Fischer, J., Gray, K., Härdtle, W., Kollmann, J., Kuhn, L., Laschke, C.J., Loos, J., Lutz, L., May, F., Meyer, M., Martin-Lopez, B., Riechers, M., Ptacek, M., Seifert, D., Schmidt, A., Sturm, L., Thiele, J., Tischew, S., Unseld, L., Venus, T., Wiesmeier, M., Kirmer, A., 2025. Proposing a social-ecological framework for successful grassland restoration in Germany—an overview and insights from the Grassworks Project. Restor. Ecol. 33 (1), e70109.

Tölgyesi, C., Vadász, C., Kun, R., Csathó, A.I., Bátori, Z., Hábenczyus, A., Erdős, L., Török, P., 2021. Post-restoration grassland management overrides the effects of restoration methods in propagule-rich landscapes. Ecol. Appl. 32 (1).

Török, P., Vida, E., Deák, B., Lengyel, S., Tóthmérész, B., 2011. Grassland restoration on former croplands in Europe: an assessment of applicability of techniques and costs. Biodivers. Conserv. 20 (11), 2311–2332.

Valkó, O., Rádai, Z., Deák, B., 2022. Hay transfer is a nature-based and sustainable solution for restoring grassland biodiversity. J. Environ. Manag. 311, 114816.

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. Biol. Conserv. 150 (1), 76–85.

Wortley, L., Hero, J.M., Howes, M., 2013. Evaluating ecological restoration success: a review of the literature. Restor. Ecol. 21 (5).

You, C., Wu, F., Gan, Y., Yang, W., Hu, Z., Xu, Z., Tan, B., Liu, L., Ni, X., 2017. Grass and forbs respond differently to nitrogen addition: a meta-analysis of global grassland ecosystems. Sci. Rep. 7 (1), 1563.