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RESEARCH ARTICLE

The relative effectiveness of different grassland restoration methods: A systematic literature search and meta-analysis

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Abstract

1. Active grassland restoration has gained importance in mitigating the dramatic decline of farmland biodiversity. While there is evidence that such operations are generally effective in promoting plant diversity, little is known about the effectiveness of the different methods applied. Restoration methods can differ in intensity of seed bed preparation, seed source and method of seed application.
2. In this systematic literature search and meta-analysis, we screened the literature for studies of the restoration of mesic grasslands in temperate Europe. We focused on active restoration experiments that included a treatment and lasted for more than 3 years. We evaluated the influence of restoration factors on plant species richness relative to non-restored controls.
3. We found 187 articles that investigated the outcome of operations aimed at actively restoring mesic temperate grasslands. Most articles focused on plants, with only 9.6% dealing with other organisms (e.g. beetles, pollinating insects). Many papers had to be excluded due to incomplete data, too short study duration and/or lack of an adequate control. This resulted in 13 articles fulfilling our criteria for inclusion, yielding a total of 56 data points for the meta-analysis.
4. Restoration actions increased plant species richness by, on average, 17.4%, compared to controls. The seed source explained a significant amount of variation in plant species richness: seeds originating from a speciose donor grassland had a positive effect. This effect was even enhanced when combined with a commercial seed mix, whereas commercial seed mixes alone had no significant effect. We did not observe any effect of other factors, such as the type of seed bed preparation or the seed application method.

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5. A seed-source obtained from species-rich grasslands seems to be key to efficient grassland restoration in mesic grasslands of temperate Europe. Even though seeds from a speciose donor grassland should be preferred over commercial seeds, associating natural and commercial seed mixes increases plant species richness. This systematic literature search further revealed two major research gaps in grassland restoration ecology: a deficit in long-term investigations as well as a deficit in studies focusing on non-plant organisms.

KEYWORDS
active restoration, literature review, mesic grasslands, plants, seed addition, soil disturbance, temperate Europe

1 | INTRODUCTION

More than 25% of Earth's continental biomes are comprised of grasslands (Blair et al., 2014; Wilsey, 2018). In Europe, grasslands make up 17% of the area of terrestrial ecosystems (Eurostat, 2018) where they are mostly semi-natural, in the sense that they depend on regular management interventions such as grazing or mowing to maintain the open habitat and to prevent encroachment by woody vegetation (Hejcman et al., 2013; Kuneš et al., 2015). Semi-natural grasslands progressively expanded since the Neolithic agricultural revolution as they were key to the development of livestock farming (Gibson, 2009). These systems have for ages harboured high plant diversity due to reduced competitive exclusion through regular biomass removal and typically offer shelter to plant species that were formerly restricted to small areas with unfavourable conditions for tree growth, such as hilly domes with shallow soils or steep slopes (Dengler et al., 2014). In addition to forage production, semi-natural grasslands provide numerous ecosystem services such as carbon capture and storage, nutrient cycling, reduction of water run-off and soil erosion (Byrne & delBarco-Trillo, 2019; Yan et al., 2019). These ecosystem services and the biodiversity of grasslands are heavily impacted by land-use intensification and land abandonment. From 1975 to 1998, the grassland cover in the EU has declined by 12% (Stoate et al., 2009; Török et al., 2018). Following the declaration of the UN Decade on Ecosystem Restoration 2021–2030 (UN Environment Programme, 2022), policy makers are now proactively supporting these systems to combat the biodiversity crisis, although grassland restoration has generally received less attention in contrast to forest or freshwater habitat restoration (Török et al., 2021).

Ecological restoration is the ‘process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed’ (Gann et al., 2019). “Passive” or “natural” restoration (sensu Atkinson & Bonser, 2020) of grasslands relies merely on the removal of the main factor responsible for the ongoing degradation, for example, cessation of fertilizer application. This restoration type may be a valid and low-cost option when adequate conditions are provided, for example, the vicinity to high quality habitats (Humann-Guilleminot et al., 2022; Prach et al., 2015). However, passive restoration may be hampered by the poor density of grassland species in the soil seed bank (Buisson et al., 2018; Turnbull et al., 2000; van Klink et al., 2017), by low dispersal capacity of the plants and by the limiting seed sources in the surrounding landscape (Bischoff et al., 2009; Münzbergová & Herben, 2005). This makes passive restoration an extremely slow process that may take several centuries for full recovery (Isbell et al., 2019; Nerlekar & Veldman, 2020). “Active” or “assisted” grassland restoration overcomes dispersal limitation through seed addition and therefore accelerates the restoration process (Atkinson & Bonser, 2020). In Europe, a multitude of techniques of active grassland restoration are currently being applied and studied. Methods differ in seed source (e.g. seeds collected from a speciose donor grassland or purchased from a commercial seed producer), seed application method (sowing of a seed mix or green hay spread out over the receiving grassland) and seed bed preparation prior to seeding (harrowing or ploughing; Albert et al., 2019; Auestad et al., 2015; Freitag et al., 2021; Hovd, 2008; Smith et al., 2017).

While several guidelines that describe best practices for grassland restoration are available (Kiehl et al., 2014; Scotton et al., 2012), there is still little quantitative evidence on the relative effectiveness of the different grassland restoration methods (Jones et al., 2018). This hampers best practice among practitioners. Literature reviews that have been carried out on this subject date back more than 10 years and typically used a qualitative or narrative synthesis approach (Hedberg & Kotowski, 2010; Kiehl et al., 2010; Török et al., 2011). The need for an actualized literature review on this topic emerged during stakeholder meetings accompanying a major ongoing grassland restoration experiment performed across Western Switzerland (Slodowicz, Auberson, et al., 2023). We thus decided to conduct a quantitative synthesis on this topic, which would not only provide better evidence-based recommendations for management but also allow addressing more specific questions that cannot be answered via non-quantitative syntheses.

In this review, we synthesize all the available knowledge on the effectiveness of different methods for restoring or re-creating species-rich semi-natural grasslands. We focus on mesic grasslands in temperate Europe due the vast area they cover and the need to restore them, as many are in a highly degraded state (Stoate et al., 2009; Török et al., 2021). First, we conducted a systematic literature search (sensu Pullin & Stewart, 2006), and second, we performed a meta-analysis, which compared the effectiveness of different restoration methods for promoting plant diversity. More specifically, we were interested in the relative effectiveness of using different sources of seeds, different methods of seeding and different ways of preparing the soil prior to seeding. This systematic literature search and meta-analysis thus provides a state-of-the-art on the topic of grassland restoration, orienting practitioners towards best practice, while also identifying research gaps to orient future investigations. To our knowledge, the present study is the first quantitative assessment ever carried out on mesic temperate European grasslands.

2 | MATERIALS AND METHODS

We followed the guidelines of the Collaboration for Environmental Evidence (Pullin & Stewart, 2006) and the ROSES standard (see ROSES form in Table S1) to conduct our systematic literature search. By doing so, we ensure repeatability of our search and screening process (Romanelli, Meli, et al., 2021; Romanelli, Silva, et al., 2021). We prepared a protocol that was peer-reviewed and published (Slodowicz et al., 2019). As some points of the original protocol had to be amended due to some unexpected issues, the following section contains the updated protocol.

2.1 | Systematic literature search

We formulated our research question according to the PICO-structure (population, intervention, control, outcome): Do different seed addition techniques for the restoration or re-creation of species rich grasslands differ in their effectiveness to enhance the diversity of plants? (see Table S2 for details on the question components). Based on the question components, we developed an initial search string, which went through a scoping process. This initial string was used in a search in the Web of Science database. We compared the search result with the reference lists of two reviews on the same topic (Hedberg & Kotowski, 2010; Kiehl et al., 2010). To achieve adequate sensitivity, we adapted the search string until no references of the reviews were missed. We used the final search string as a template for our database searches and adapted it accordingly to the requirements of the respective databases: (grassland* OR meadow* OR pasture*) AND (restor* OR seed addition OR seed transfer OR hay transfer OR sow* OR strew*) AND (*diversity OR enhance* OR success OR richness OR establish*). We conducted the database searches between 26 November 2019 and 16 March 2020 in Web of Science Core Collection, Scopus, Directory of open access journals (DOAJ) and eThOs. In addition, we used the "Publish or perish" software (Harzing, 2007) to search articles in Google Scholar and retained the first 1000 hits. A detailed overview of the search string development and database searches can be found in the Supporting Information (Table S3, Appendix S1).

To complement the database search, we looked for other publications and grey literature in Google, organizational websites and through direct requests to authors. The searches and requests were done in English, French, German and Polish. We removed duplicates automatically using the JabRef Reference Manager (JabRef Development Team, 2021).

2.2 | Article screening

Screening was done on title, abstract and full-text level by two reviewers (DS, AD). A third reviewer (JYH, co-author of this paper) checked for inclusion consistency using Cohen's Kappa (Pullin & Stewart, 2006) on a subsample of 500 articles from each reviewer, respectively. A Kappa score of >0.6 indicated high consistency between reviewers. At title and abstract levels, we included all restoration studies that were conducted within temperate Europe. At the full text level, the articles had to fulfil our eligibility criteria for inclusion (Table 1). We

TABLE 1 Eligibility criteria at full-text screening.

Eligible populations	Mesic grasslands in temperate Europe, which we define as being within the Cfb-zone according to the Köppen–Geiger climate classification system (Kottek et al., 2006)
Eligible interventions	Grassland restoration (e.g. from a species-poor grassland) or re-creation (e.g. on formerly arable land) with one or more of the following seeding methods: • hay transfer from a species-rich donor grassland • seeds originating from a species-rich donor grassland from the respective region • commercial seed mixture especially designed for restoration or re-creation purposes of grasslands And Seed bed preparation prior to seeding through either ploughing or harrowing. Note that we excluded studies with over-sowing directly over an extant vegetation cover with no soil disturbance as this method was recurrently proven as particularly ineffective for grassland restoration
Eligible comparators	Control sites/plots with no intervention, that is, no seed/hay added and no seed bed preparation (species-poor reference) or sites/plots with seed bed preparation or ex-arable land, but without seed addition (natural regeneration). The control sites are managed in the same way as the intervention plots. In case of before-after studies, the before-data was used as control
Eligible outcomes	Mean plant species richness with measure of variance per treatment and study year
Eligible types of study design	Experimental studies with either before-after or control-intervention design with at least three replicates per treatment and a study duration of at least 3 years. For field scale studies without replication, there must be at least three vegetation survey plots (we acknowledge that this is considered pseudo replication)

distinguished three grassland habitat types: dry, wet and mesic. We considered grassland habitats to be "dry" if the substrate was coarse or sandy with low water retention capacity and low amount of nutrients in the soil (e.g. Wolff et al., 2017). We considered grasslands to be "wet" if they were peat or fen meadows (e.g. Klimkowska et al., 2010) or alluvial meadows (e.g. Schmiede et al., 2009). All other grasslands were considered mesic and therefore eligible populations. In our meta-analysis, we have intentionally excluded short-term studies shorter than 3 years duration to reduce confounding factors. In effect, the first 2 years after restoration are typically characterized by a rise in species richness (Albert et al., 2019; Baasch et al., 2016; Freitag et al., 2021). This is often due to the presence of ruderal species, which have become dominant in the seed bank after perturbation (Valkó et al., 2022). Once the grassland species become more dominant, the number of ruderal species diminishes (Albert et al., 2019). This is reflected in a slight decline in species richness after the second year of restoration (Freitag et al., 2021). For this reason, we focused on the mid-term, thus ensuring that the plant community had become more stable by then. Yet, to identify research gaps in a later phase, we compiled a separate list of all excluded European studies at full-text screening. All articles on European grassland restoration excluded during the full-text screening step are provided in Table S4.

2.3 | Data extraction and moderators

The geographic location of each restoration site was recorded and, if necessary, changed into decimal degrees. If the site coordinates were not provided, we looked for a locality (such as a city, village or a protected area) in the site description of the respective article and determined the coordinates from Google Maps. As potential moderator variables (effect modifiers) we included the control type, type of study design, seed source, seed application method, seed bed preparation (seed bed preparation is requisite for efficient seed addition), former land-use, restoration duration, number of experimental replicates, as well as vegetation survey plot size (see Table 2 for a detailed definition of each moderator). These moderator variables are either linked to applied aspects of grassland restoration (e.g. seed source), which are relevant for practitioners, or to experimental aspects (e.g. control type). As response variables we extracted the mean plant species richness and a measure of variance (which was converted to standard deviation if necessary) from the restored and control plots. We extracted these from summary tables, calculated it from raw data or extracted it from the figures using the WebPlotDigitizer (Rohatgi, 2021). We contacted the authors by e-mail to request missing data if relevant data were unavailable in, or not extractable from the study. A list of data sources used in the study is provided in the Data sources section.

2.4 | Meta-analysis

We performed model selection utilizing different effect sizes, model structures and according to the influence of scale (i.e. the size of vegetation survey plots) as recommended by Spake et al. (2021). Specifically, we tested for scale-dependence in our results across modelling approaches to select the most parsimonious model approach and structure. The vegetation plot size ranged from 0.25–25 m^2, but we did not detect scale dependency in our data. We selected a model structure employing weighted random effects using the log response ratio (lnRR) as effect size (see Figures S1–S3 for details). Article ID was included as a random effect to account for variation between studies. We fitted the models with restricted maximum likelihood method (REML). We applied the Knapp and Hartung adjustment, where the test statistics of individual coefficients are based on the t distribution instead on the default Z distribution, which in turn may reduce Type I error (Assink & Wibbelink, 2016). To evaluate the effect of moderators on the selected model, the residual heterogeneity (QE), degrees of freedom and p-value were extracted. To check whether the effect sizes are influenced by a given moderator, we extracted the F-value with its degrees of freedom and p-value from the test of moderators (Viechtbauer, 2010). We plotted the effect sizes and 95% confidence intervals of all moderators and their respective categories when they significantly influenced the effect sizes (i.e. $p < 0.05$ at test of moderators). Furthermore, the p-uniform test and the Fail-Safe N Analysis were conducted to check for publication bias. All analyses were performed with R version 4.1.1 (R Core Team, 2021) using the METAFOR (Viechtbauer, 2010) and PUINFORM packages (van Aert, 2018).

3 | RESULTS

3.1 | Systematic literature search

All literature searches combined yielded 12,153 records (Appendix S1). After title and abstract screening, and the removal of duplicates, 532 articles remained (Figure S4). The Kappa Scores were 0.85 and 0.69 (for DS/JYH and AD/JYH, respectively), indicating high inclusion consistency between reviewers. At full-text screening we identified 187 articles which studied active grassland restoration in temperate Europe (Table S4). Among these articles, 18 were excluded because they focused on other organisms than plants, in most cases either beetles or pollinating invertebrates. Further articles had to be excluded due to, in decreasing order of importance, missing data, a type of grassland habitat different from our target, study duration shorter than 3 years and inadequate or no experimental control (Figure 1).

3.2 | Meta-analysis

We selected 13 articles that met our rules for inclusion in the quantitative meta-analysis. This yielded 56 data points, that is, effect sizes, from 44 sites for our meta-analysis. Overall, 88% of the study sites were in the United Kingdom, Germany or the Czech Republic.

TABLE 2 Overview of all moderator variables that were extracted from the included studies for the meta-analysis and brief explanations of the different categories. The numbers in brackets after each category indicate the amount of data points of the respective category. The total amount of data points is $n = 56$.

Moderator variable	Categories	Explanation
Seed bed preparation	Harrow (17)	Soil disturbance up to 10 cm depth
	Plough (39)	Soil disturbance beyond 10 cm depth
Seed application method	Hay (14)	Only possible if seed source was a species-rich donor grassland. The donor grassland was mown, and the fresh hay was spread over the area that was to be restored
	Seed (42)	Possible for both seed source types. The seeds were harvested if the seed source was a species-rich donor grassland, for example, with a brush harvester
Seed source	Species rich donor grassland (21)	A species-rich grassland in the vicinity of the restored area
	Commercially purchased seed mix (9)	Seeds provided by a seed producer. The seed mix contains typical grassland species
	Both (26)	Both above mentioned seed sources were applied together
Study design	Block study (28)	Restoration treatments and control were replicated on one field
	Field scale study (28)	A whole field/grassland was restored
Control type	Species-poor reference (17)	A control site on the same or neighbouring grassland, which did not undergo any treatment (no seed bed preparation, no seeding) and which was managed the same way afterwards as the restored sites. We considered experiments with before-after design as well as "species-poor reference" if the restored area was formerly already a grassland
	Natural regeneration (39)	Either a site with seed bed preparation but without seeding on a former grassland or no seeding only if the site was formerly arable land
Former land-use	Arable (35)	The area was used as crop before restoration, that is, regular soil interventions. It can be assumed that the seed bank should be rich in ruderal species. In some of these cases, seeding occurred directly on the open soil with no additional seed bed preparation
	Grassland (21)	The area was either a hay meadow or pasture before restoration but had a low amount of typical grassland species. In most cases, the low species number was due to overexploitation (e.g. high fertilizer input, high mowing frequency)
Restoration duration		Time span between the year of establishment and the year of data collection. When there was a series of time points of data collection, we included only the most recent one
Replicates		For block studies: amount of treatment replicates For field scale studies: amount of vegetation survey plots
Vegetation survey plot size		Size of the plot used for the vegetation sampling in m^2

Further sites were situated in Norway, Ireland, France and Italy (Figure 2).

The overall effect of grassland restoration measures on plant species richness was positive (lnRR = 0.34, 95% CI 0.13–0.55, $p = 0.002$, Figure 3), with a mean increase in plant species richness of 17.4% compared to control. The variance within certain articles was quite large, which was mainly explained by different restoration methods experimentally tested within a single article (Figure 3). The moderator "seed source" showed a significant moderating effect ($F = 17.48$, $p < 0.001$, AIC = 212.08, Table 3). We observed a positive effect when commercial seeds and seeds from a speciose donor grassland were combined (lnRR = 0.52, 95% CI 0.22–0.82, $p < 0.001$, Figure 4). The effect was less pronounced when the seeds applied originated from a speciose donor grassland only (lnRR = 0.28, 95% CI −0.01–0.58, $p = 0.060$). In contrast, the use of commercial seeds alone showed no significant effect on the species richness of restored grasslands (lnRR = 0.31, 95% CI −0.07–0.69, $p = 0.110$). The number of seeded plant species in the commercial mixes ranged from 15 to 66, but we could not detect any influence of that seed diversity on the effect size (Figure S5).

"Restoration duration", ranging from 3 to 16 years, had a significant moderating effect as well ($F = 13.50$, $p = 0.001$, AIC = 233.09, Table 3) and was slightly negative (lnRR = −0.02, 95% CI −0.03 to −0.01, $p < 0.001$, Figure S6). However, 77% of all data points stemmed from studies whose duration was typically 3–6 years. Not surprisingly, the moderating effect of "restoration duration" disappeared when only studies with 3–6 years duration were included in the model ($F = 2.80$, $p = 0.100$). Furthermore, all data points with a study duration of more than 6 years originated from three articles. These three experimental studies had been performed on arable land (prior to restoration) and had "natural regeneration" as control. In contrast to a species-poor reference as control, naturally regenerated control plots might possibly overcome the species richness of the treatment plots (Prach et al., 2014), which is reflected in a lower or even negative effect size.

"Former land use" and "control type" showed significant moderating effects as well ($F = 5.07$, $p = 0.030$, AIC = 239.17

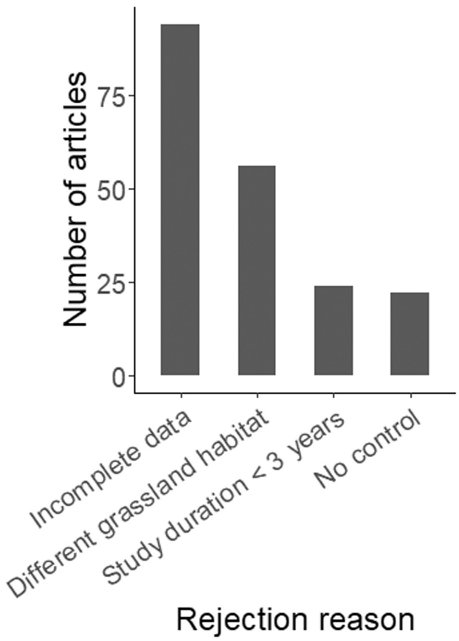

FIGURE 1 Articles dealing with grassland restoration studies in temperate Europe which had to be excluded from the meta-analysis, with reason for rejection ($n = 174$). Note that more than one reason can apply to a single article. Articles with missing data did not report all the information that was necessary for our meta-analysis, or the data was not extractable from the figures. A different grassland habitat indicates a non-mesic habitat, that is, either dry or wet habitat.

and $F = 4.78$, $p = 0.030$, AIC = 239.30, respectively; Table 3, Figure 4). In addition, these two moderators were highly correlated ($r = 0.85$, $p < 0.001$) and yielded similar effect sizes. Data points having grasslands as land use before restoration had frequently a species-poor reference as a control (81%) and showed a positive effect of restoration for both land use and control type (lnRR = 0.44, 95% CI 0.23–0.64, $p < 0.001$ and lnRR = 0.47, 95% CI 0.26–0.69, $p < 0.001$, respectively). Data points with arable land before restoration and natural regeneration as control had a smaller effect (lnRR = 0.21, 95% CI −0.01 to 0.42, $p < 0.070$ and lnRR = 0.24, 95% CI 0.04–0.44, $p < 0.020$, respectively). All other potential moderators did not exhibit any moderating effects (Table 3). The p-uniform test (L.pb = −3.44, $p = 0.99$) and the Fail-Safe N Analysis (4603) revealed that there is little evidence for publication bias, indicating that our results are robust.

4 | DISCUSSION

Our systematic literature search and meta-analysis provide quantitative evidence that active grassland restoration or re-creation that rely on seed addition can enhance plant species richness of mesic grasslands in temperate Europe, supporting previous narrative reviews on this topic (Hedberg & Kotowski, 2010; Kiehl et al., 2010). Several variables, such as the type of seed source, the past land-use of the site selected for experimental restoration, as well as the type of control employed all emerged as key factors influencing restoration success. However, our analysis could not detect any further difference in effectiveness between the other restoration options under scrutiny: for instance, neither the seed application method (direct addition of seeds by sowing vs. green hay collected from a donor meadow and spread all over the receiving area) nor

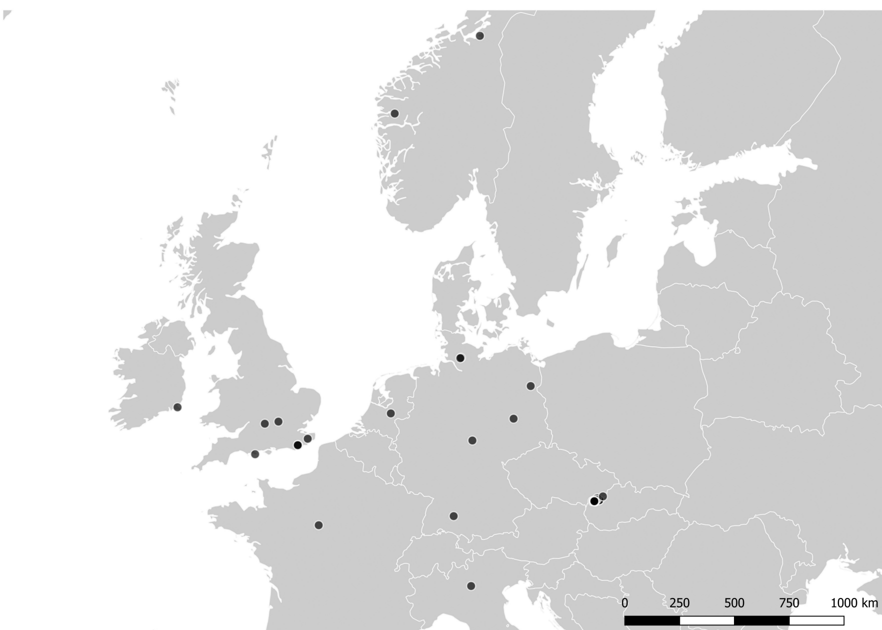

FIGURE 2 Location of the study sites included in the meta-analysis.

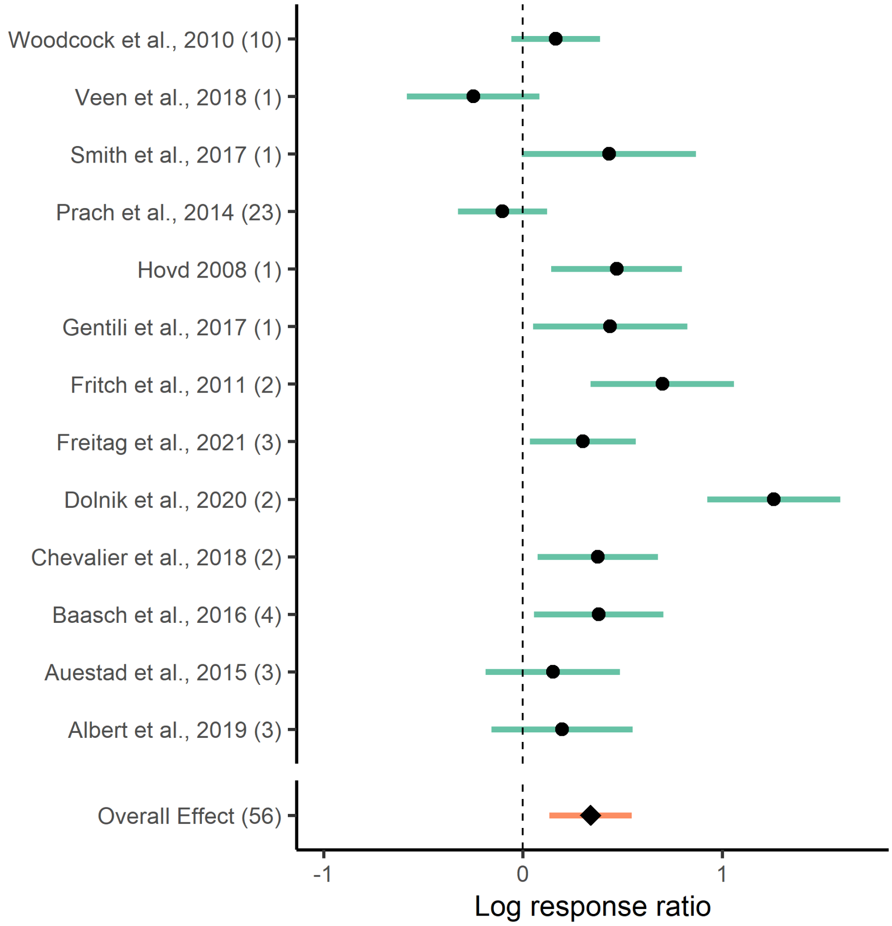

FIGURE 3 Forest plot with the mean effect sizes and 95% confidence interval for each study (in green), as well as the overall effect, across studies (in orange), of active grassland restoration on plant species richness. The brackets indicate the number of data points.

TABLE 3 Output summary for the moderator analysis. The first column gives the name of a given moderator variable (see Table 2 for details). The following three columns provide the residual heterogeneity (*QE*) together with its degrees of freedom (*df*) and *p*-value (*p*). The three columns afterwards provide the *F*-value (*F*) from the test of moderators with its degrees of freedom (*df*) and *p*-value (*p*). The moderator variables are ranked by their respective AIC value (last column). The model formula had the following structure: rma.mv(lnRR ~ moderator, RE = ~1 | study id/m^2, REML), where "lnRR" is the log response ratio effect size, "RE" the weighted random effect, study "id" the unique identifier of each study and "m^2" the species richness of a respective control site. These analyses were performed with the METAFOR package for R (Viechtbauer, 2010). See the "meta-analysis" subsection in the Methods part for more detail.

	Test for residual heterogeneity			**Test of moderators**			
Moderator	***df***	***QE***	***p***	***df***	***F***	***p***	**AIC**
Seed source	53	1055.96	<0.001	2	17.48	<0.001	212.08
Restoration duration	54	897.52	<0.001	1	13.50	<0.001	233.09
Control type	54	795.59	<0.001	1	5.07	0.03	239.17
Former land-use	54	654.25	<0.001	1	4.78	0.03	239.30
Plot size	54	950.21	<0.001	1	1.24	0.27	240.38
Seed bed preparation	54	847.45	<0.001	1	2.91	0.09	240.90
Study design	54	900.76	<0.001	1	0.76	0.39	241.32
Full model	55	1102.26	<0.001	NA	NA	NA	241.57
Replicates	54	1034.36	<0.001	1	0.29	0.59	242.34
Seed application method	54	1005.76	<0.001	1	0.29	0.59	245.96

the intensity of the seed bed preparation (ploughing vs. harrowing) were significant factors. The present study conveys clear recommendations for conservation and restoration management (see Shackelford et al., 2021 for a meta-analysis on dry grassland restoration).

4.1 | Mid-term effectiveness depends on seed source

The choice of the seed source—that is, from a species-rich donor grassland, a commercial seed mixture or a combination of both—had

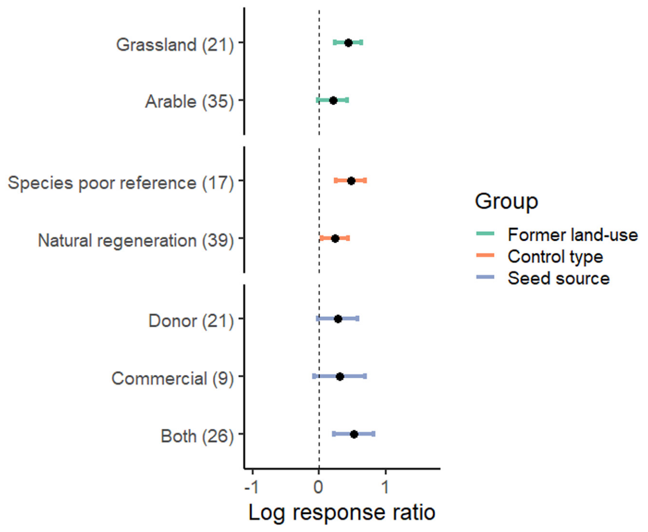

FIGURE 4 Forest plot with the mean effect sizes and 95% confidence interval of relevant moderators and the overall effect of active grassland restoration on plant species richness. The number in brackets represents the number of data points per category. See Table 2 for a definition of the different moderators.

an effect on the restoration outcome. The highest positive effect size was obtained when mixing seeds from a speciose donor grassland together with commercial seeds, as already demonstrated by Baasch et al. (2016). These authors had added seeds of target plant species obtained from a local commercial seed producer, which did not originally occur in their donor species-rich grassland: this boosted the final plant species richness by 68%, which was established in the restored meadow after 5 years. Thus, restoration relying only on seeds from a donor grassland is less effective than the combined approach, but this method might be easier to implement in practice, especially if appropriate donor grasslands are available in the near surrounding landscape. Although the moderator "commercial seeds" was statistically non-significant (confidence interval just overlapping 0), its effect size was very close to that of seeds collected from donor grasslands. Despite a wide range in the number of seeded species (15–66; Freitag et al., 2021; Veen et al., 2018), we could not detect any effect of that moderator. The latter study compared the effects of low and high-diversity seed mixes, showing that a more speciose seed mix resulted in higher species diversity in the restored meadow after a few years (Kirmer et al., 2012). More robust conclusions could have been drawn if the number of seeded species was known. In practice, this number is mostly provided for commercial seed mixes, but hardly for directly harvested seeds from species-rich donor grasslands. Furthermore, while propagules coming from the surrounding may play an important role in regions where a high density of species-rich grasslands still remains in the landscape, for example, in eastern Czech Republic (Prach et al., 2015), the included studies come from Central Europe where remnant species-rich grasslands are scarcer (Stoate et al., 2009), and therefore, their contribution is expected to be low. In practice, the mixed approach associating natural and commercial seed mixes thus represents the best option for restoration operations, this despite the extra logistical and financial costs it entails.

4.2 | Previous land-use, control type, seed bed preparation and method of seed application

The type of land-use before restoration also influences the magnitude of the effectiveness of restoration treatments. This was correlated with the type of control used in the respective studies. The positive effects of restoration operations tended to be less marked when the control was undergoing a spontaneous natural regeneration after being harrowed or ploughed. Indeed, the harrowed/ploughed control offers favourable abiotic conditions for germination and natural regeneration might be effective if a variety of propagules can arrive spontaneously from the surrounding landscape (Albert et al., 2019; Prach et al., 2014) or from the neighbouring, seeded plot. Consequently, using natural regeneration as a control in a favourable non-degraded species-rich landscape might underestimate the actual restoration effect. Thus, the diminishing effect of age since restoration, compared to the control that we observed in the longer-term studies with a duration beyond 6 years, should be interpreted with caution. In effect, these long-term studies used natural regeneration as control, where the species richness of the control plots increased over time.

Our results further suggest that the intensity of the seed bed preparation does not influence the plant species richness that is achieved in the mid-term by restoration. A similar result was obtained 16 years after restoration of floodplain meadows (Sommer et al., 2023). Nevertheless, seed-bed preparation remains a crucial step in active grassland restoration. There is a consensus that the seed bed must absolutely be prepared through harrowing or ploughing in order to allow seed germination (Durbecq et al., 2021; Freitag et al., 2021). In effect, over-sowing over an extant vegetation layer is not a good option for mesic grasslands: the seeded plants would be exposed to unfavourable abiotic conditions for seedling recruitment and mostly be outcompeted by the already established plant community (Freitag et al., 2021; Kiehl et al., 2010). This is why over-sowing was not even considered in our review. Few studies of mesic grasslands have compared the effects of the intensity of seed bed preparation on restoration outcomes (for wet meadows, see Bischoff et al., 2018). In practice, the method used for seed bed preparation mostly depends on the original soil conditions (e.g. deep vs stony soils), which eventually determine the selection of the agricultural machinery for field operations.

The seed application method—direct seed sowing vs spread of fresh hay all over the receiving meadow—did not per se seem to influence species richness in the mid-term. This was unexpected as seeding with green hay might favour seed germination, and therefore subsequent plant establishment, by creating a more favourable microhabitat. For example, a hay layer can reduce soil evapotranspiration, especially during the dry summer months when restoration experiments take place, or provide protection from extreme cold events in alpine or northern areas (Havrilla et al., 2020). On the contrary, seeding with seeds only might cover a wider range of species compared to green hay, for example, through collection from different sources or throughout different seasons (Albert et al., 2019).

However, these differences in the initial phase of establishment seem to be balanced out after several years (Baasch et al., 2016).

4.3 | Research gaps and opportunities

From 187 articles that studied active grassland restoration in temperate Europe, we could only include 13 in our meta-analysis, which somehow limits generalization of the main results. We used species richness as a metric, as frequently done for biodiversity syntheses due to its simplicity and wide availability (Marchand et al., 2021; Nerlekar & Veldman, 2020). However, we noticed during the screening process that while species richness was mentioned in the study, data or results were sometimes not quantitatively reported for a proper integration into a meta-analysis. In addition, some studies had different focuses. For example, some look at vegetation differences between the restored area and a nearby reference site (Prach et al., 2014), others focus on ecosystem services (De Cauwer et al., 2006), select target species (Johanidesová et al., 2015) or refer to the cover of different functional groups (Conrad & Tischew, 2011). While these metrics are important to investigate the effect of a treatment on different aspects of the restoration outcomes, the diversity of metrics we encountered across studies, with little consistency between them, represented a major impediment to a proper meta-analysis. Researchers and practitioners active in the field of restoration ecology ought to render their data publicly available for future syntheses (FAIR prescriptions; Wilkinson et al., 2016). The Global Restore Project, a publicly accessible platform (Ladouceur & Shackelford, 2021), has for objective to standardize such datasets, checking notably for taxonomic consistency. Based on more solid foundations, future syntheses will be able to incorporate more fine-scaled information and help with interoperability of restoration monitoring schemes. While we acknowledge that 13 articles being included in our meta-analysis is a limitation, our strict inclusion criteria led to a meta-analysis that incorporates the most robust results in the context of active restoration of mesic grasslands in temperate Europe.

We also identified several research gaps, which present opportunities for future research. Most studies so far focused on the effect of restoration measures on the plant community whereas only a few focused on other organisms such as beetles (Woodcock et al., 2010, 2012), pollinating insects (Ouvrard et al., 2018; Redpath-Downing et al., 2013) and soil microfauna (Norton et al., 2019; Resch et al., 2019). Invertebrate studies show that the restoration of phytophagous beetles was most successful where grassland restoration achieved the highest diversity of, notably, flowering plants species (Woodcock et al., 2010), this due to more foraging opportunities for pollinating insects (Ouvrard et al., 2018; Redpath-Downing et al., 2013).

It was rapidly clear to us that there is a lack of long-term studies, which is probably due to limited research funding timelines. This lack in long-term data represents a serious impediment to properly assess the success of restoration operations. The majority of studies span 3–6 years, which remains insufficient for a sound evaluation. In effect, it may take decades, if not centuries in extreme conditions, for a restored grassland to reach its climactic state (Isbell et al., 2019; Nerlekar & Veldman, 2020). This calls for better endowed and especially longer-term supportive funding for restoration experiments on grasslands specifically, and more generally for other types of ecosystems.

Finally, there was a geographical bias in our dataset. Most studies originated from the United Kingdom, Germany and the Czech Republic. Other countries that harbour vast areas of grasslands, such as France, Italy, Poland, Switzerland or Ireland harboured only few, if any, restoration studies of mesic grasslands. This pattern cannot be merely explained by a bias towards papers published in English as our literature search was carried out in four European languages, covering a wide palette of temperate European countries.

4.4 | Restoration implications and recommendations

Our results highlight the importance of the seed source when restoring or re-creating grasslands. Restoration success in terms of plant species richness is most likely achieved when combining seeds from a species-rich grassland with commercial seeds. Yet, using seeds from a species-rich grassland only is also effective. In contrast, using commercial seeds only had a slightly lesser, but statistically non-significant effect. In practice, grassland restoration can be limited by the availability of seeds, which reduces in some cases the possibility of choosing the appropriate seed source. When no local seed source is available, a commercial seed mix might be the sole option. In Europe, seed transfer zones were recently created to account for local ecotypes and intraspecific variation (Cevallos et al., 2020; Durka et al., 2017) and seed certificates were introduced to make locally produced seeds more widely available for practitioners (Mainz & Wieden, 2019). However, supply remains insufficient to cover the current high demand for restoration operations. This concerns in particular rare or endangered plant taxa, for which seed production is complicated by issues revolving around obtaining permit for plant/seed collection (Ladouceur et al., 2018). We therefore recommend the use of commercial seeds only in areas with a limited provision of a local natural seed source and insofar as a regional origin is ensured. Similarly, relying on commercial seeds with an unknown provenance is not an option since it might contribute to introduce genetically different and locally maladapted populations (Höfner et al., 2021). Last but not least, commercial seed mixes can be quite expensive (Török et al., 2011). The reliance on species-rich grasslands as donors appears thus to be the best solution for restoring species-rich mesic grasslands. Beyond its positive effects on the restored plant community, hay transfer also benefits the invertebrate community that might be transported with the freshly mown grass (Elias & Thiede, 2008; Stöckli et al., 2021; Wagner, 2004).

AUTHOR CONTRIBUTIONS

Daniel Slodowicz, Jean-Yves Humbert and Raphaël Arlettaz conceived the study and designed its methodology; Daniel Slodowicz, Aure Durbecq, Emma Ladouceur and René Eschen collected the data

and did the screening; Daniel Slodowicz, Emma Ladouceur and Jean-Yves Humbert analysed the data; Daniel Slodowicz led the writing of the manuscript with major contributions by Aure Durbecq. All authors contributed critically to the drafts, with thorough editing by Jean-Yves Humbert and Raphaël Arlettaz, and gave final approval for publication.

STATEMENT ON INCLUSION

Our study is a review based on a meta-analysis of secondary rather than primary data. As such, there was no local data collection. However, the geographical distribution of the authorship team broadly represents the major regions of interest in the meta-analysis, supporting the inclusion of data from peer-reviewed studies published in local languages and ensuring the appropriate interpretation of data and results from each region. In addition, the necessity for an up-to-date literature review in the field of active grassland restoration arose during accompanying group committee meetings of a grassland management project in Switzerland. The group was composed of experts from multiple disciplines, which included, among others, representatives of local and national environment and agriculture offices. Members of the group provided numerous inputs on practical issues based on their own field experience.

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CONFLICT OF INTEREST STATEMENT

None.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.2v6wwpzt1 (Slodowicz, Durbecq, et al., 2023) and sources provided in Data Sources.

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Note that the three Articles by Woodcock, Vogiatzakis, et al. (2010), Woodcock, Edwards, et al. (2010) and Woodcock et al. (2012) shared several study sites, which we included in our meta-analysis. Their effect sizes are summarized in Figure 3 as "Woodcock et al. (2010)".

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Model types.

Figure S2. Outcome measures and plot size.

Figure S3. Influence of scale.

Figure S4. Flow diagram.

Figure S5. Effect commercial seeds.

Figure S6. Effect restoration duration.

Table S1. ROSES form.

Table S2. PICO question components.

Table S3. Search string development.

Table S4. Excluded European grassland restoration articles.

Appendix S1. Database and other searches with excluded articles.

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Systematic review “Grassland restoration”

Supplementary material

Exploratory plots to check for the effect of different effect size measures and model types on the overall effect (Figure S1). We also checked for scale dependence in our data set (Figures S2 and S3). For details on the methods see Spake et al., 2021

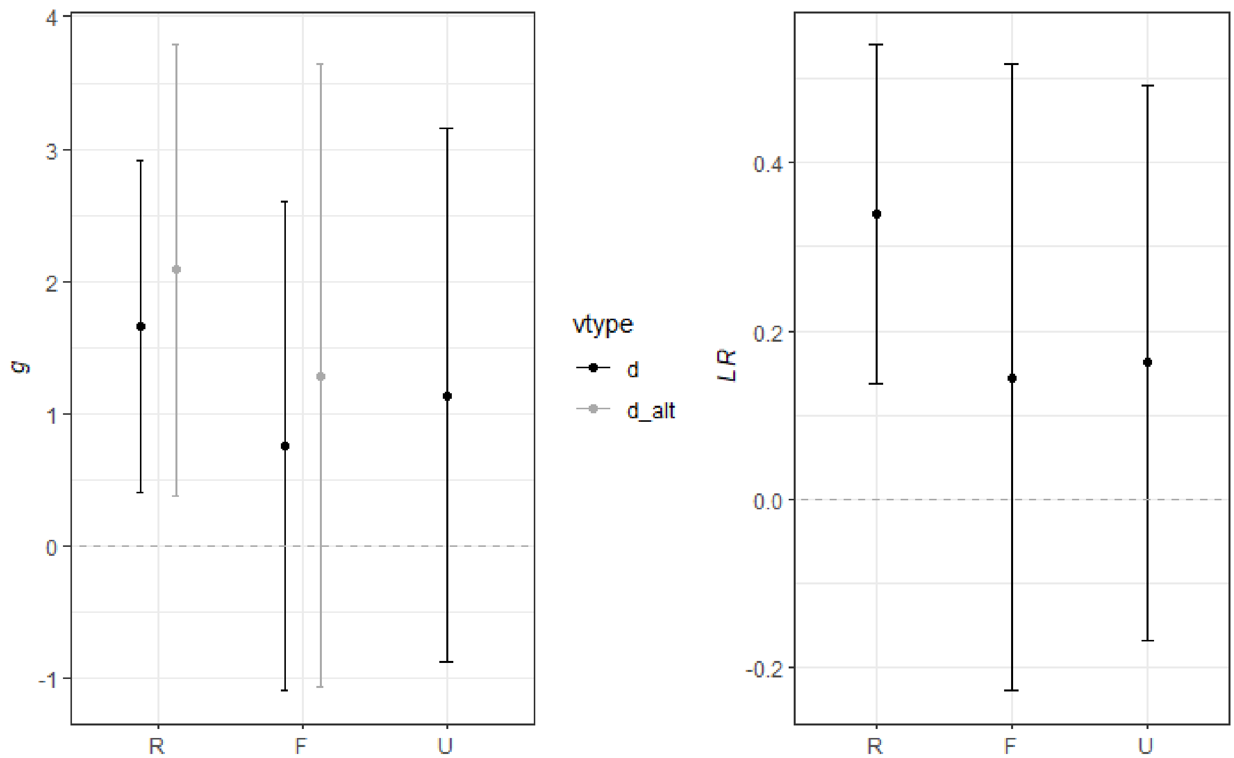

Figure S1 Meta-estimates as calculated with hedges' g (left) and log response ratio LR (right). These are global meta-effect sizes (±95% CI) from models with no moderators. For each effect size measure, we used random effects weighted (R), fixed effects weighted (F) and unweighted (U) models. Weighted meta-analyses of hedges' g (R, F) used variance estimators equal to the conventional variance (black) and also an alternative variance calculation (Hedges, 1982) (grey, d_alt). The difference is that the formula for the conventional variance contains the standardized mean difference, whereas the formula for d_alt is independent of it. There is no effect when the 95% CI band overlaps with zero.

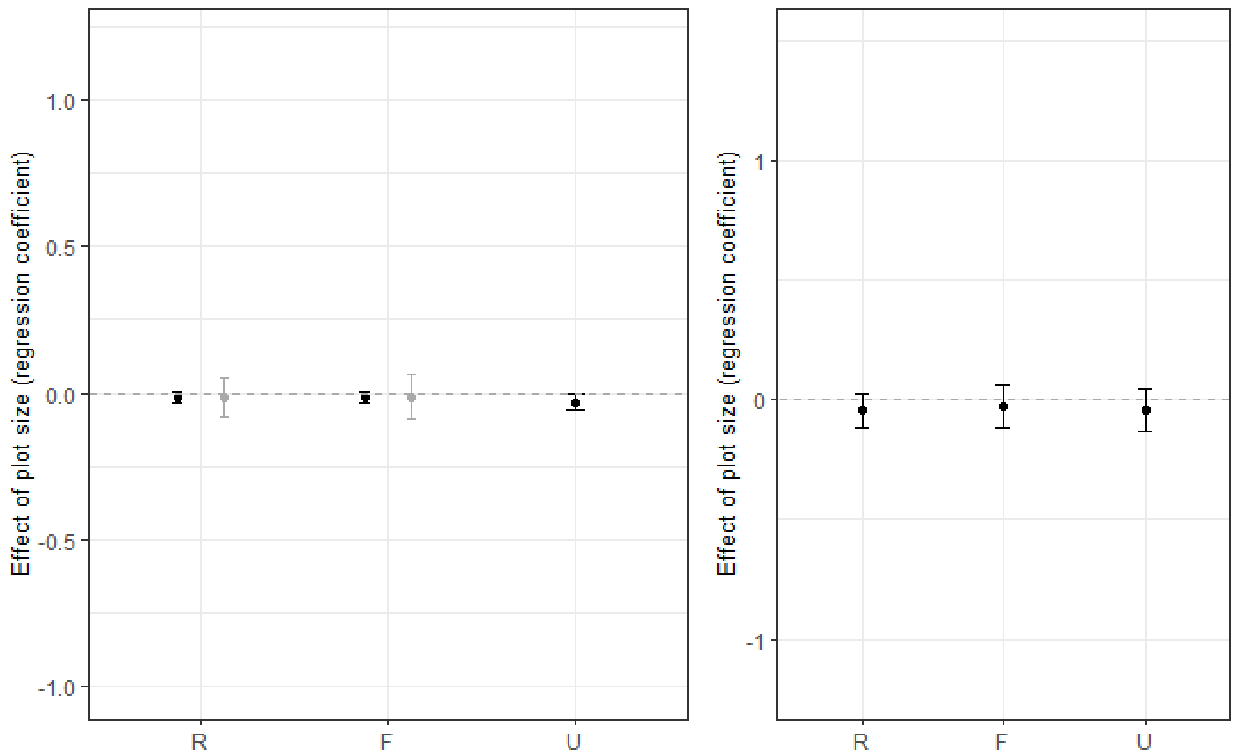

Figure S2 Effects of plot size on effect sizes of active grassland restoration on plant species richness. See figure caption of Fig. S1 for explanations.

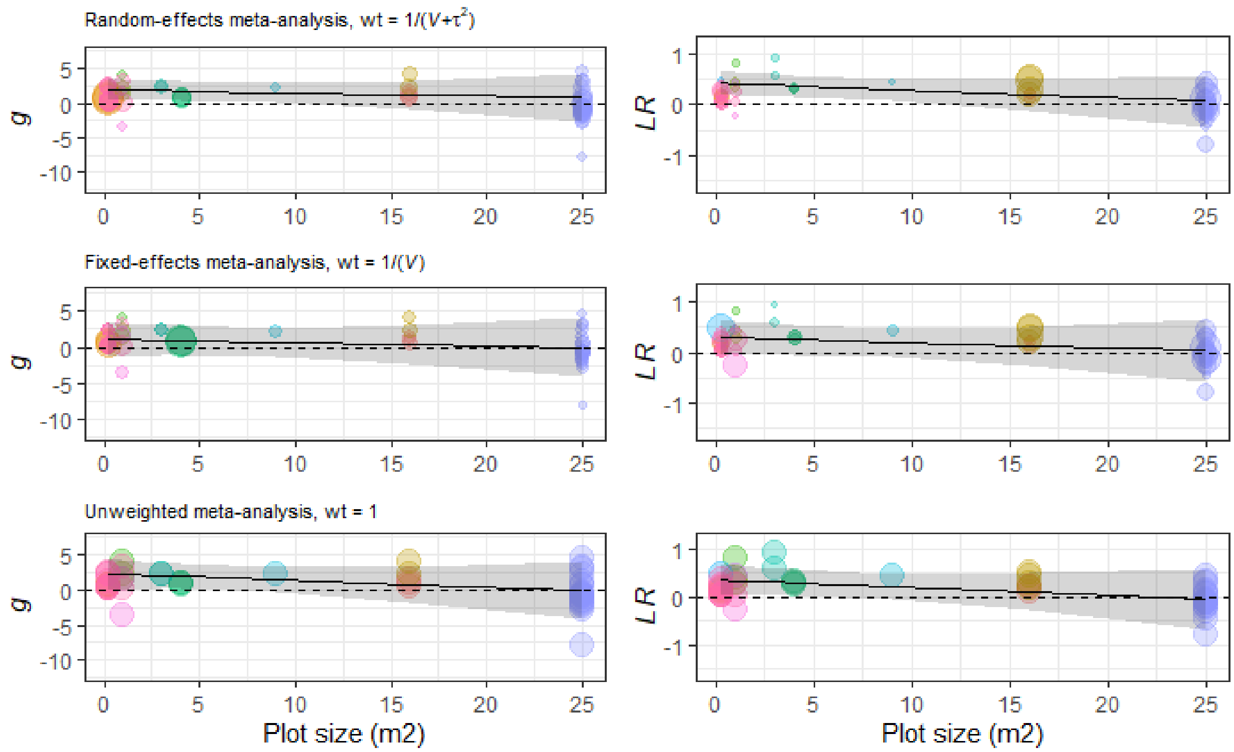

Figure S3 Influence of scale (plot size) on effect-size metric (columns) and model type (rows), for active grassland restoration on plant species richness. Meta-regressions have 95% prediction intervals (grey shading) based on uncertainty only in the plot-size effect. Point size is proportional to relative study weight for each meta-regression, with colours distinguishing different publications. Variances for hedges' g were estimated by the conventional variance measure (see figure caption of Fig. 1).

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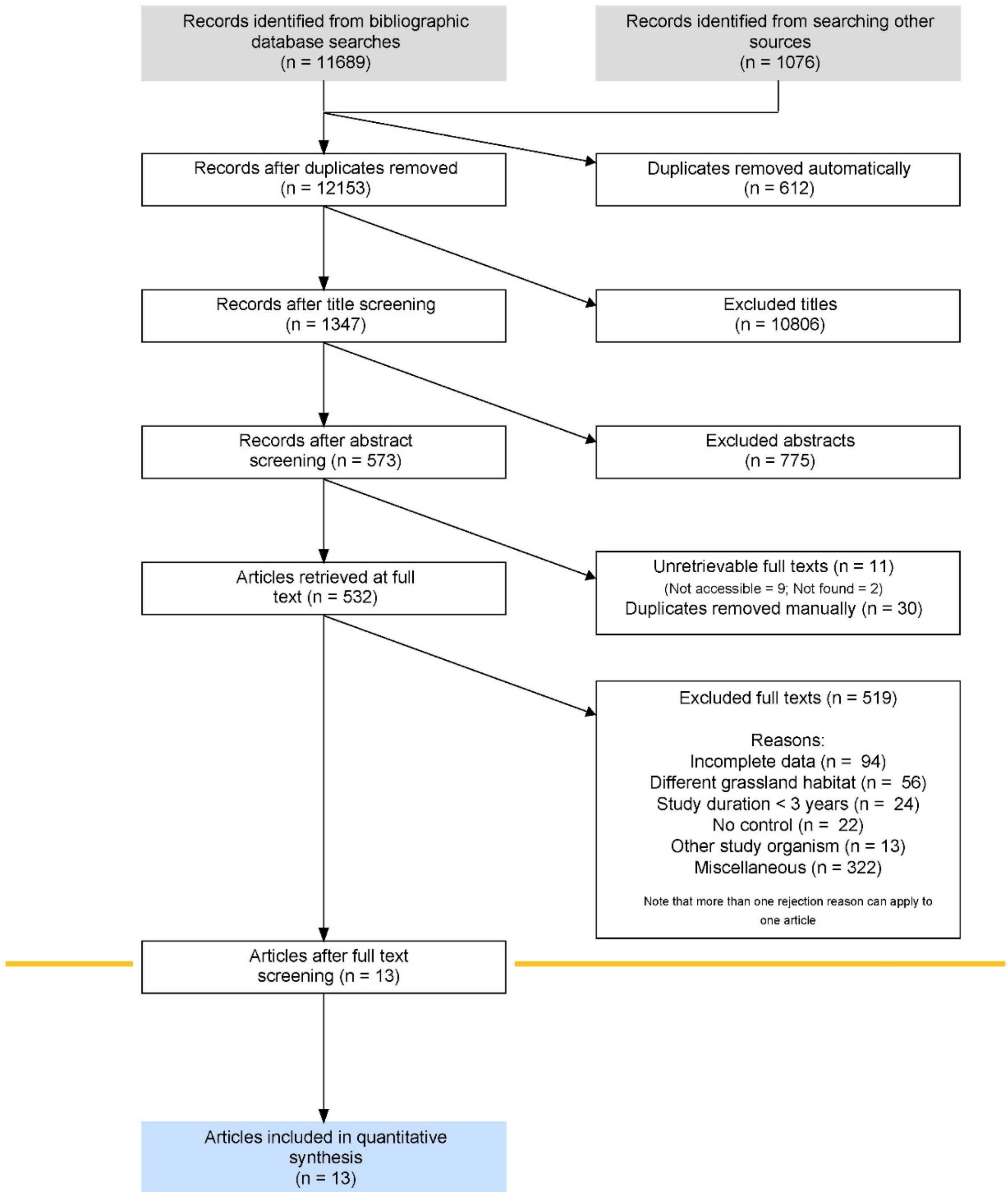
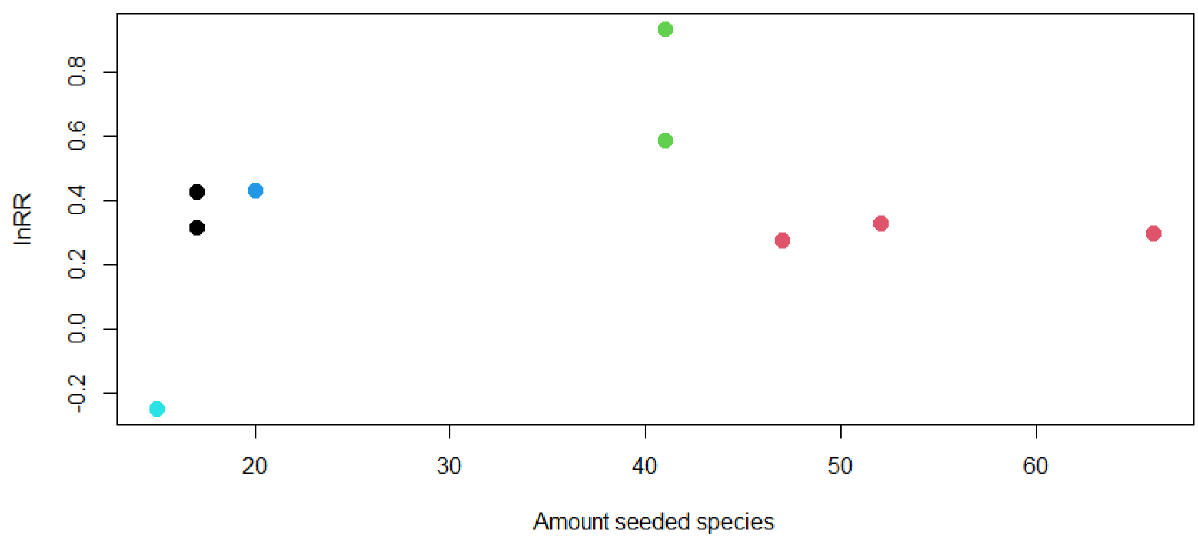
Figure S4 Flow chart showing the different screening steps. At full-text screening we compiled a separate list with excluded grassland restoration studies from temperate Europe to identify research gaps (n = 187, not shown here). This list as well as a detailed overview of all excluded articles at all screening steps can be found in appendix S2.



Supplementary material

Figure S5 Scatterplot for the number of seeded species (x-axis) and the effect size in log response ration (lnRR, y-axis). Each point represents a single data point from the meta-analysis and the colours represent articles, meaning that points with the same colour belong to the same article. The data points in this plot are only having commercial seed mixes as seed source. There was no effect of the amount seeded species on the effect size (F(7) = 0.52, P = 0.5).



Supplementary material

Figure S6 Meta-regression for the study duration in years (x-axis) and the effect size in log response ratio (lnRR, y-axis) including the regression line with 95% confidence interval. Points represents a single data point from the meta-analysis and are scaled in proportion to their weight. We used the regplot() function from the *metafor* package (Viechtbauer, 2010) to create this plot.