

1           **Fit by design: Developing substrate-specific seed mixtures for**  
2                                   **functional dike grasslands**

3                                   Markus Bauer\*, Jakob K. Huber, Johannes Kollmann

4   Restoration Ecology, TUM School of Life Sciences, Technical University of Munich, Germany

5   \* Corresponding author: [markus1.bauer@tum.de](mailto:markus1.bauer@tum.de)

6

## 7 **Abstract**

- 8 1. Sowing is a well-established restoration technique to overcome dispersal limitation. Site-specific  
9 seed mixtures are most effective to achieve functional communities. This is especially important  
10 if the restored vegetation has to protect critical infrastructure like roadsides and dikes. Here, an  
11 improved seed–substrate combination will secure slope stability, reduce mowing efforts, and  
12 generate species-rich grasslands.
- 13 2. A factorial field experiment addressed this topic on a dike at River Danube in SE Germany in  
14 2018–2021. Within 288 plots, we tested three sand admixtures, two substrate depths, two seed  
15 densities and two seed mixture types (mesic hay meadow, semi-dry calcareous grassland) in north  
16 and south exposition, and measured the recovery completeness by calculating the successional  
17 distance to reference sites, the persistence of sown species, and the Favourable Conservation  
18 Status (FCS) of target species.
- 19 3. Overall, the sown vegetation developed in the desired direction, but a recovery debt remained  
20 after four years, and some plots still showed similarities to negative references from ruderal sites.  
21 In north exposition, hay meadow-seed mixtures developed closer to the respective reference  
22 communities than dry-grassland mixtures.
- 23 4. In south exposition, the sown communities developed poorly which might be due to a severe  
24 drought during establishment. This initial negative effect remained over the entire observation  
25 period.
- 26 5. Sand admixture had a slightly positive effect on target variables, while substrate depth, seed  
27 density and mixture type had no effects on species persistence or FCS.
- 28 6. Synthesis and applications: Site-adapted seed mixtures make restoration more effective.  
29 However, applying several seed–substrate combinations might foster beta diversity. Furthermore,  
30 additional management efforts are recommended, as they might be necessary to reduce the  
31 recovery debt, as well as re-sowing after unfavourable conditions.

32 **Keywords**

33 Artificial soil mixture

34 Dry grasslands

35 Ecological restoration

36 Levee

37 Persistence

38 River embankment

39 Sowing

40 Species composition

41

## 42 **Introduction**

43 Grasslands can support an exceedingly high biodiversity and they provide several ecosystem services  
44 (Bardgett et al., 2021; Dengler et al., 2014). However, they are globally endangered (Bardgett et al.,  
45 2021), and in Europe, calcareous grasslands and hay meadows are red-listed habitats (Category 3,  
46 ‘vulnerable,’ Janssen et al., 2016). Restoration is seen as a key factor to sustain biodiversity and  
47 ecosystem services (*Convention on Biological Diversity (CBD)*, 2014; United Nations, 2019), and sowing  
48 is a well-established approach to establish species-rich grasslands (Kiehl et al., 2010). Sowing high-  
49 diversity mixtures of local provenance produced by specialized companies is a promising way to scale up  
50 restoration efforts (Freitag et al., 2021), and to overcome dispersal filters (Myers & Harms, 2009; Orrock  
51 et al., 2023). However, there are still open questions about adjusting seed mixtures to specific site  
52 conditions and future climate conditions (Török et al., 2021).

53 Restoration ecology can increase the predictability of restoration approaches (Mouquet et al., 2015) by  
54 using rigorous, repeatable, and transparent experiments based on advanced theory, which will finally  
55 strengthen evidence-based restoration (Cooke et al., 2018; Wainwright et al., 2018). Local site conditions  
56 and the restoration method are key predictors for vegetation development after sowing (Brudvig et al.,  
57 2017), while habitat and biotic filtering are the main assembly factors which can be manipulated by the  
58 choice of seed–substrate combinations (Török & Helm, 2017). This means a close adaptation of the  
59 substrate to the niche of the target species or of the seed mixtures to the characteristics of the chosen  
60 substrate. Suitable substrates reduce habitat filtering of the seeded species, while specific seed mixture  
61 minimises competitive exclusion of desired species and simultaneously prohibiting invasive species  
62 (Funk et al., 2008). Modifying seed mixtures to match the site conditions could be based on functional  
63 plant traits (Balazs et al., 2020; Funk et al., 2008; Laughlin, 2014), although this is not easy to implement  
64 (Bauer et al., 2022; Merchant et al., 2022). This challenge is particularly interesting for artificial  
65 substrates that are used in urban areas (Bauer et al., 2022), in quarries (Chenot-Lescure et al., 2022), or on  
66 dikes (Liebrand & Sykora, 1996).

67 Dikes are promising sites for the restoration of species-rich grasslands because they can increase habitat  
68 area and connectivity of semi-natural grasslands and therefore significantly contribute to biodiversity  
69 conservation in agricultural landscapes (Bátori et al., 2020). Steep slopes with different exposition,  
70 contrasting substrate layers and dense swards for erosion protection characterise these habitats (Bátori et  
71 al., 2016; Berendse et al., 2015; Husicka, 2003). Dikes can reconcile several ecosystem functions  
72 including both flood security and rich biodiversity (Teixeira et al., 2022), which can be fostered by an  
73 adapted seed–substrate combination.

74 The aim of this study is to identify the best combinations of seed mixtures and substrates for vital and  
75 species-rich grasslands on north- and south-exposed dike slopes. An experiment was set up to test  
76 different substrate depths, sand admixtures, seed densities, and mixture types. We expected a better  
77 development of dry grassland in the south exposition with shallow and sandy substrates, and of mesic  
78 meadows in north exposition on less sandy and deeper substrates. For steep slopes, e.g., on dikes, high  
79 seed densities are recommended for successful vegetation establishment (Kleber-Lerchbaumer et al.,  
80 2017), albeit without experimental evidence.

81 The success of restoration, i.e., the difference from desired conditions, is evaluated by comparing the  
82 species composition with reference sites (cf. Brudvig et al., 2017), since the successional distance to  
83 reference grasslands describes the recovery completeness (Rydgren et al., 2019). Furthermore, we  
84 observed the persistence, which is the presence of the sown species monitored over three consecutive  
85 years (Wilsey, 2021). Finally, the Favourable Conservation Status (FCS) was calculated which  
86 distinguishes habitat-characteristic diversity and non-typical derived diversity (Helm et al., 2015). Based  
87 on four years of monitoring, we tested the following hypotheses:

- 88 1. Site conditions on northern vs southern dike slopes facilitate establishment of mesic or dry  
89 grassland mixtures, respectively.
- 90 2. Nutrient reduction by sand addition and shallow substrates increase the establishment of dry-  
91 grassland compared to mesic seed mixtures.
- 92 3. Reduced soil resources benefit target species of species-rich grasslands.

93 4. High seed densities increase the establishment of sown plants and suppress non-target species.

94

## 95 **Materials and methods**

### 96 **Field experimental design**

97 Specific combinations of seed mixtures and substrates ('seed–substrate combinations') were tested on a  
98 dike at the Danube River in SE Germany (Figure 1; 314 m a.s.l.; WGS84: lat/lon, 48.83895/12.88412).  
99 The climate of the region is temperate-suboceanic with a mean annual temperature of 8.4 °C and an  
100 annual precipitation of 984 mm (Deutscher Wetterdienst, 2021). During the study, three exceptionally dry  
101 years (2018–2020) occurred (Appendix A1, Hari et al., 2020), as well as three minor floods, which,  
102 though, did not reach the plots (Appendix A1). The substrates consisted of calcareous sand (0–4 mm) and  
103 agricultural soil obtained from a nearby dike construction site near the village of Steinkirchen. A big  
104 roller mixed both components and an excavator put the substrates in the prepared plots.

105 The target vegetation types were lowland mesic hay meadows and semi-dry calcareous grassland (EUNIS  
106 codes: R22, R1A, Chytrý et al., 2020; Arrhenatherion elatioris and Cirsio-Brachypodium pinnati  
107 according to the EuroVegChecklist: CM01A, DA01B, Mucina et al., 2016). The species pool of hay  
108 meadows and dry grasslands consisted of 55 and 58 species, respectively. The seeds were received from a  
109 commercial producer of autochthonous seeds (Co. Krimmer, Pulling). From these species pools, 20  
110 species were selected for each plot in a stratified, randomised manner (Appendix A2). Each mixture  
111 contained seven grasses (60wt% of total seed mixture), three legumes (5%) and ten herbs (35%) (Table  
112 1). The hay-meadow mixtures had higher community-weighted means (CWM) for specific leaf area  
113 (SLA), lower for seed mass, and higher for canopy height than the dry-grassland mixtures (Appendix A3).

114 The south-exposed plots were sown in mid-April 2018 and the north exposition 14 days later. In October  
115 2018, *Bromus hordeaceus* was sown as a nursery grass to provide safe sites under drought conditions. In  
116 late-April 2018 due to the drought, the south exposition was protected by a geotextile consisting of straw  
117 chaff (350 g m<sup>-2</sup>) which was removed after two weeks due to unsatisfactory effects on seedling  
118 emergence. The management started with a cut at 20 cm height without hay removal in August 2018,  
119 followed by standard deep cuts with hay removal in July 2019 and 2020.

120 We used 288 plots of the size 2.0 m × 3.0 m, vertically oriented, halfway up the dike slopes, distributed  
121 over the north and south exposition, and arranged in six blocks (=replicates). The experiment used a split-  
122 plot design combined with a randomised complete block design (Figure 1). The split plot was created by  
123 the two expositions of the dike, where all 24 treatment combinations were tested, i.e., sand admixtures (0,  
124 25, and 50%), soil depths (15 vs. 30 cm), the two seed mixture types, and two seed densities (4 vs. 8 g m<sup>-2</sup>,  
125 cf. Kiehl et al., 2010; Kleber-Lerchbaumer et al., 2017).

126 Below the substrate, a 5-cm thick drainage layer of gravel (0–16 mm) was installed. Soil samples of the  
127 three substrates from both expositions were tested by mixing several sub-samples from different plots.  
128 The sand admixture changed the soil texture, increased the C/N ratio, reduced calcium carbonate, but did  
129 hardly change the pH which was within the weak alkaline range (Table 2). The pH and C/N ratio were  
130 within the recommended range, as well as the clay ratio of the 25% sand admixture and the substrate  
131 depth of 30 cm (Husicka, 2003). Phosphate and potassium were rather scarce for agricultural soils, but  
132 magnesium showed high concentrations (Bayerisches Landesamt für Landwirtschaft (LfL), 2022).

### 133 **Vegetation surveys**

134 The vegetation was surveyed in June or July 2018–2021 (Braun-Blanquet, 1964) and the Londo scale was  
135 used (Londo, 1976). The establishment rates of species were recorded in Appendix A4. Establishment  
136 success was high with 48 species of the species pool of hay meadows (87%) and 46 (79%) of dry  
137 grasslands recorded by 2021, which are rather good ratios (cf. Hedberg & Kotowski, 2010); the species  
138 established in 31 ± 22% (mean ± SD) of their sown plots. In total, 274 vascular plant species were found  
139 (Appendix A5).

140 The recovery completeness was described by the successional distance which quantifies the distance of a  
141 plot to the average reference site in the ordination ( $d_{ji,0}$ , Rydgren et al., 2019, Figure 2). Persistence was  
142 derived from the ‘species losses’ component of the temporal beta-diversity index (TBI;  $1 - B_{\text{sor}}$ ) which  
143 was calculated by comparing the seed mixtures with the respective species composition of each year  
144 using Sørensen dissimilarity (Legendre, 2019). The Favourable Conservation Status (FCS) is the ratio of



145 characteristic and derived diversity measured as species richness (Helm et al., 2015). Characteristic  
146 diversity consists of species that belong to a habitat-specific species pool and derived diversity consists of  
147 all other species. The habitat-specific species pool consisted of all sown species and other typical species  
148 of mesic and dry grasslands (Appendix A5).

149 To compare the restoration outcomes with real references and not solely with seed mixtures, vegetation  
150 surveys were extracted from sPlotOpen (Sabatini et al., 2021) and our own surveys on the Danube dikes  
151 in the surroundings (Bauer et al., 2023a). We selected six dry grassland plots (EUNIS code R1A, Chytrý  
152 et al., 2020) within SE Germany from sPlotOpen and 98 plots of our own survey, which included also hay  
153 meadows (R22), and as a negative reference ruderal, dry and anthropogenic vegetation (V38).

## 154 **Statistical analysis**

155 A non-metric multidimensional scaling ordination (NMDS) with Sørensen dissimilarity was used to  
156 visualise variation in species composition in space and time. Seven species were excluded because they  
157 had an accumulated cover over all plots of <0.5%. Finally, 343 species were included in the ordination.

158 To measure the effects of the treatments on our three response variables, we calculated Bayesian linear  
159 mixed-effects models (BLMM) with the random effect plot nested in block with the Cauchy prior (see  
160 Lemoine, 2019). Furthermore, we included as a fixed effect the botanists, who recorded a certain plot. For  
161 the simple effects of the treatments, we chose plausible weakly informative priors. To evaluate the  
162 influence of the priors, prior predictive checks and models with non-informative priors were calculated.

163 For the computation, we used four chains, a thinning rate of two, 5,000 iterations for warm-up, and  
164 10,000 in total. We used the Markov Chain Monte Carlo method (MCMC) with the no-U-turn Sampler  
165 (NUTS). For evaluating the computation, the convergence of the four chains was checked using trace  
166 plots and evaluating  $R$ -hat values, and MCMC chain resolution by the effective sampling size (ESS).

167 Posterior predictive checks were done with Kernel density estimates histograms of statistics skew and  
168 leave-one-out (LOO) cross-validation (see Gabry et al., 2019). Finally, the models were compared with  
169 the Bayes factor (BF) and Bayesian  $R^2$  values (Gelman et al., 2019).

170 Data, code and the entire model specifications and evaluations are stored on GitHub and presented in an  
171 easily accessible document for scrolling through (Bauer et al., 2023b). There, the sections are referenced  
172 to the Bayesian analysis reporting guidelines (BARG, Kruschke, 2021). All analyses were performed in R  
173 (Version 4.2.2, R Core Team, 2022), with the functions ‘brm’ from the package ‘brms’ (Bürkner, 2017)  
174 for model calculation, several functions from ‘brms’ and ‘bayesplot’ (Gabry & Mahr, 2022) for model  
175 evaluation, and ‘metaMDS’ from ‘vegan’ for the ordination (Oksanen et al., 2022).

176

## 177 **Results**

### 178 **Hay meadows on north exposition closer to reference**

179 The ordination showed the species composition of seed mixtures and the development of the plots during  
180 four years (Figure 2). The NMDS confirmed that the seed mixtures were variable, albeit distinctive for  
181 hay meadows and dry grasslands and confirming the intended direction of the vegetation development. As  
182 one exception, hay meadows in south exposition did not develop towards their seed-mixture  
183 compositions.

184 The reference sites had a larger variation than the seed mixtures and were close to the seed mixtures but  
185 hardly overlapped (Figure 2). The positions of the reference sites shifted to the left in comparison to the  
186 seed mixtures, which means in the direction of early-successional stages. Nonetheless, they still differed  
187 from the negative references of ruderal vegetation. Negative references were only available on the south  
188 exposition and they were located in the NMDS between the positive reference sites and the state of  
189 restored plots in 2021. Nevertheless, 33% of the 288 plots reached the state of the target habitat types by  
190 2021 (EUNIS code R22, R1A, Chytrý et al., 2020). Hay meadow-seed mixtures led to a closer  
191 development to hay-meadow references than dry grasslands to their references (Figure 3A, 4A). This was  
192 especially the case in north exposition (Figure 2).

### 193 **Weak effects of substrates and seed density**

194 We could identify a statistically clear positive effect of the sand admixture on the persistence of sown  
195 species and on the recovery rate, but no effects of seed density or substrate depth (Figure 3). The posterior  
196 distributions are also shown in the interaction plots that separate exposition and survey year (Figures 4).  
197 For all three response variables, the vegetation developed positively after one year, while the recovery  
198 rate slowed down in the following years. Both expositions revealed similar trends but for all responses,  
199 the values were clearly lower in south exposition, e.g., persistence values were on average more than 46%  
200 higher in north exposition (Figure 4B). The interactions of restoration treatments were neither clear nor

201 strong. Persistence of both seed mixture types was slightly positively affected by sand admixture in north  
202 exposition (+ 6–7 ± 4%, Figure 4B).

## 203 **Discussion**

### 204 **Success of the restoration approaches**

205 The seed mixtures and their positive reference sites were similar but hardly overlapped (Figure 2). The  
206 position on the ordination suggests that the seed mixture represents a late-successional stage compared to  
207 the references. The NMDS shows a slightly better adaptation of hay meadows to the north exposition than  
208 of dry grasslands (Figure 4A). This can be expected from the requirements of hay meadows for mesic  
209 conditions, which can be provided on north-exposed dike slopes (Bátori et al., 2020; Oberdorfer, 1993).  
210 In southern exposition, the plots of hay meadows developed rather towards dry grassland references  
211 which indicates an ineffective restoration due to a non-adapted seed mixture.

212 The vegetation developed generally in the desired direction but was still distinct from positive references  
213 and seed mixtures after four years. In the south exposition, the plots were rather similar to the negative  
214 reference of dry ruderal vegetation. The gap between goal and restoration outcome was also shown for  
215 other sowing experiments or restorations (Engst et al., 2016; Kaulfuß et al., 2022; Mitchley et al., 2012)  
216 or for dike vegetation compared with semi-natural reference grassland (Bátori et al., 2016). This result is  
217 not surprising since the ‘recovery debt’ is a general phenomenon of grassland restoration (Jones et al.,  
218 2018; Moreno-Mateos et al., 2017).

### 219 **General effects of treatments and exposition**

220 Restoration on agricultural soils can have limited success due to high nutrient loads (Walker et al., 2004)  
221 but mixing with a mineral component need not necessarily improve the outcome (Chenot-Lescure et al.,  
222 2022). Similarly to a study in France, sand admixture reduced nutrient loads and led to higher persistence  
223 of sown species while a 50% admixture did not further increase this effect. In addition, the effect only  
224 appeared in north exposition and the effect size of about 6% in the 4<sup>th</sup> year of restoration was rather small.

225 The Favourable Conservation Status (FCS) was hardly affected by the sand admixture, which corresponds  
226 to an experiment in a quarry (Chenot-Lescure et al., 2022). Substrate depth did not significantly affect  
227 persistence or FCS, similarly to earlier studies (Baer et al., 2004; Husicka, 2003). Larger differences in  
228 soil depths might be necessary to observe negative effects by thicker substrate layers as was shown for  
229 prairies (Dornbush & Wilsey, 2010) or a substrate depth of <15 cm, since most roots occur in the topsoil  
230 on dikes (Vannoppen et al., 2016). Seed density had also no clear effect on persistence and FCS which  
231 fits the results of Kaulfuß et al. (2022), who found that a certain amount of seeds is necessary for a  
232 successful establishment of target species, but higher densities do not further improve the outcome, but  
233 rather have a slightly negative effect.

234 The vegetation in south exposition had a different species composition, which confirms the findings of  
235 Bátori et al. (2016) in Hungary. However, the differences might also be due to methodical reasons, since  
236 the geotextile, which had been implemented on the southern slope, was removed after two weeks. This  
237 was unfortunate for at least some seedlings, and amplified by the intense drought in summer 2018 and  
238 2019 (cf. Hari et al., 2020; Larson et al., 2021; Orrock et al., 2023). The lasting negative effect on  
239 persistence and FCS on the southern slope suggests a legacy effect of adverse weather conditions after  
240 sowing as observed by other studies (Groves et al., 2020; Stuble et al., 2017). These conditions during the  
241 establishment phase might have led to a special trajectory (Suding et al., 2004), and probably levelled the  
242 distinction of the seed mixture types in south exposition.

### 243 **No interaction effect of seed–substrate combinations**

244 Our aim was to identify perfect seed–substrate combinations regarding restoration effectiveness and  
245 biodiversity. For evaluating effectiveness, we measured the persistence of the sown species, and FCS for  
246 investigating plant biodiversity. However, we could not identify an interaction effect for neither one of  
247 these indices. We would have expected a better performance of hay-meadow seed mixtures with lower  
248 sand admixture and for dry grasslands with higher sand admixture. Our results suggest that, at least after  
249 four years, the substrate conditions are within the range of both seed mixture types (hay meadows vs dry

250 grasslands). Although, both types are clearly phytosociologically and functionally distinct, they are still  
251 relatively close, because they contain shared species and develop under similar site conditions with  
252 modified sub-associations (Appendix A3, Husicka, 2003; Oberdorfer, 1993). Other grassland studies  
253 could identify more or less clear interactions of opposing habitat preferences or functional traits along the  
254 gradients of productivity, moisture and nutrients (Freitag et al., 2021; Kaulfuß et al., 2022; Zirbel &  
255 Brudvig, 2020). However, these studies did not work with an experimental set up of different seed–  
256 substrate combinations, but analysed the result of habitat and biotic filtering after 1, 5 and 15yrs,  
257 respectively. Furthermore, the non-existence of ideal combinations could be explained by priority effects  
258 that means that the species of the imperfect-adapted seed mixture type could establish earlier and pre-  
259 empted the available niches for the species of related habitat types (Fukami, 2015).

260

## 261 **Conclusions**

262 Our results suggest that adapted seed mixtures can increase restoration effectiveness by sowing hay  
263 meadows in the north but not necessarily in south exposition of dikes. Furthermore, the reduction of the  
264 nutrient load through sand admixture was positive, albeit with small effect size. The question remains if  
265 sand admixture is the most efficient restoration measure to promote diversity on dikes. Increasing seed  
266 density on dike slopes does not appear to be necessary, and soil depths of 30 cm are not adverse compared  
267 to 15 cm thick substrates.

268 There were no perfect seed–substrate combinations and thus we conclude that a variation of seed mixture  
269 types and different substrates along restoration sections would promote biodiversity more than a single  
270 uniform solution (Bauer et al., 2023a; Holl et al., 2022). Negative effects of drought in the sowing season  
271 might require re-sowing. To close the recovery debt, the management adaptation might be promising  
272 since this is a crucial factor beside the restoration approach and the site characteristics (Grman et al.,  
273 2013; Tölgyesi et al., 2021). For example, the introduction of sheep grazing on the experimental plots,  
274 which already exists in the surroundings, will modify the disturbance regime and improve dispersal.

275 Overall, our results support the finding that restored dike grasslands can promote biodiversity in  
276 agricultural landscapes (Bátori et al., 2020). However, the recovery debt highlights the fact that restored  
277 grasslands cannot substitute old-growth grasslands (Nerlekar & Veldman, 2020).

278

## 279 **Acknowledgements**

280 We would like to thank our project partners Dr. Markus Fischer, Frank Schuster, and Christoph Schwahn  
281 (WIGES GmbH) as well as Klaus Rachl and Stefan Radlmair (Government of Lower Bavaria) for  
282 numerous discussions on restoration and management of dike grasslands. Fieldwork was supported by  
283 Clemens Berger and Uwe Kleber-Lerchbaumer (Wasserwirtschaftsamt Deggendorf). We thank Holger  
284 Paetsch, Simon Reith, Anna Ritter, Jakob Strak, Leonardo H. Teixeira, and Linda Weggler for assisting  
285 with the field surveys or soil analyses in 2018–2020. The German Federal Environmental Foundation  
286 (DBU) supported MB with a doctoral scholarship.

## 287 **Author contribution**

288 JH and JK designed the experiment. JH did the surveys in the years 2018–2020, and MB in 2019 and  
289 2021. MB did the analyses and wrote the manuscript. JK and JH critically revised the manuscript.

## 290 **Open research**

291 Data and code are stored on Zenodo (Bauer et al., 2023b). Model evaluation is stored on GitHub:  
292 [https://github.com/markus1bauer/2023\\_danube\\_dike\\_experiment/tree/main/markdown](https://github.com/markus1bauer/2023_danube_dike_experiment/tree/main/markdown)

## 293 **Funding**

294 MB was funded by a doctoral scholarship of the German Federal Environmental Foundation (DBU)  
295 (No. 20021/698). The establishment of the experiment and the vegetation surveys were financed by the  
296 WIGES GmbH in the years 2018–2020 (No. 80 002 312).

297



## 298 **References**

- 299 Baer, S. G., Blair, J. M., Collins, S. L., & Knapp, A. K. (2004). Plant community responses to resource  
300 availability and heterogeneity during restoration. *Oecologia*, *139*, 617–629.  
301 <https://doi.org/10.1007/s00442-004-1541-3>
- 302 Balazs, K. R., Kramer, A. T., Munson, S. M., Talkington, N., Still, S., & Butterfield, B. J. (2020). The  
303 right trait in the right place at the right time: Matching traits to environment improves restoration  
304 outcomes. *Ecological Applications*, *30*, e02110. <https://doi.org/10.1002/eap.2110>
- 305 Bardgett, R. D., Bullock, J. M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan,  
306 G., Fry, E. L., Johnson, D., Lavalley, J. M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X.,  
307 Zhou, H., Ma, L., Ren, W., ... Shi, H. (2021). Combatting global grassland degradation. *Nature*  
308 *Reviews Earth & Environment*, *2*, 720–735. <https://doi.org/10.1038/s43017-021-00207-2>
- 309 Bátor, Z., Kiss, P. J., Tölgyesi, C., Deák, B., Valkó, O., Török, P., Erdős, L., Tóthmérész, B., &  
310 Kelemen, A. (2020). River embankments mitigate the loss of grassland biodiversity in agricultural  
311 landscapes. *River Research and Applications*, *36*, 1160–1170. <https://doi.org/10.1002/rra.3643>
- 312 Bátor, Z., Körmöczi, L., Zalatnai, M., Erdős, L., Ódor, P., Tölgyesi, C., Margóczy, K., Torma, A., Gallé,  
313 R., Cseh, V., & Török, P. (2016). River dikes in agricultural landscapes: The importance of secondary  
314 habitats in maintaining landscape-scale diversity. *Wetlands*, *36*, 251–264.  
315 <https://doi.org/10.1007/s13157-016-0734-y>
- 316 Bauer, M., Huber, J., & Kollmann, J. (2023a). Beta diversity of restored river dike grasslands is strongly  
317 influenced by uncontrolled spatio-temporal variability. *EcoEvoRxiv*.  
318 <http://dx.doi.org/10.32942/X2959J>
- 319 Bauer, M., Huber, J., & Kollmann, J. (2023b). Data and code of Bauer et al. (2023) bioRxiv. v1.0.1.  
320 *Zenodo*. <https://doi.org/10.10.5281/zenodo.7713396>
- 321 Bauer, M., Krause, M., Heizinger, V., & Kollmann, J. (2022). Using crushed waste bricks for urban  
322 greening with contrasting grassland mixtures: No negative effects of brick-augmented substrates  
323 varying in soil type, moisture and acid pre-treatment. *Urban Ecosystems*, *25*, 1369–1378.  
324 <https://doi.org/10.1007/s11252-022-01230-x>
- 325 Bayerische Vermessungsverwaltung. (2023). *BayernAtlas. Open data. Digitales Orthophoto 40cm*  
326 *(DOP40). License CC-BY-4.0*.  
327 <https://geodaten.bayern.de/opengeodata/OpenDataDetail.html?pn=dop40>
- 328 Bayerisches Landesamt für Landwirtschaft (LfL). (2022). *Leitfaden für die Düngung von Acker- und*  
329 *Grünland. Gelbes Heft. Stand: 2022*.  
330 [https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/2022\\_08\\_iab\\_info\\_gelbes\\_h](https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/2022_08_iab_info_gelbes_heft.pdf)  
331 [eft.pdf](https://www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/2022_08_iab_info_gelbes_heft.pdf)
- 332 Berendse, F., Ruijven, J. van, Jongejans, E., & Keesstra, S. (2015). Loss of plant species diversity reduces  
333 soil erosion resistance. *Ecosystems*, *18*, 881–888. <https://doi.org/10.1007/s10021-015-9869-6>
- 334 Braun-Blanquet, J. (1964). *Pflanzensoziologie: Grundzüge der Vegetationskunde* (3rd ed.). Springer,  
335 Wien–NewYork. <https://doi.org/10.1007/978-3-7091-8110-2>
- 336 Brudvig, L. A., Barak, R. S., Bauer, J. T., Caughlin, T. T., Laughlin, D. C., Larios, L., Matthews, J. W.,  
337 Stuble, K. L., Turley, N. E., & Zirbel, C. R. (2017). Interpreting variation to advance predictive  
338 restoration science. *Journal of Applied Ecology*, *54*, 1018–1027. [https://doi.org/10.1111/1365-](https://doi.org/10.1111/1365-2664.12938)  
339 [2664.12938](https://doi.org/10.1111/1365-2664.12938)
- 340 Bundesanstalt für Geowissenschaften und Rohstoffe (Ed.). (2005). *Bodenkundliche Kartieranleitung* (5th  
341 ed.). Schweizerbart, Stuttgart. ISBN 978-3-510-95920-4.
- 342 Bürkner, P.-C. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of*  
343 *Statistical Software*, *80*, 1–28. <https://doi.org/10.18637/jss.v080.i01>
- 344 Chenot-Lescure, J., Jaunatre, R., Buisson, E., Ramone, H., & Dutoit, T. (2022). Using various artificial  
345 soil mixtures to restore dry grasslands in quarries. *Restoration Ecology*, *30*, e13620.  
346 <https://doi.org/10.1111/rec.13620>

- 347 Chytrý, M., Tichý, L., Hennekens, S. M., Knollová, I., Janssen, J. A. M., Rodwell, J. S., Peterka, T.,  
348 Marcenò, C., Landucci, F., Danihelka, J., Hájek, M., Dengler, J., Novák, P., Zukal, D., Jiménez-  
349 Alfaro, B., Mucina, L., Abdulhak, S., Ačić, S., Agrillo, E., ... Schaminée, J. H. J. (2020). EUNIS  
350 habitat classification: Expert system, characteristic species combinations and distribution maps of  
351 european habitats. *Applied Vegetation Science*, 23, 648–675. <https://doi.org/10.1111/avsc.12519>  
352 *Convention on Biological Diversity (CBD): Aichi biodiversity targets 14 and 15*. (2014).  
353 <https://www.cbd.int/sp/targets/>
- 354 Cooke, S. J., Rous, A. M., Donaldson, L. A., Taylor, J. J., Rytwinski, T., Prior, K. A., Smokorowski, K.  
355 E., & Bennett, J. R. (2018). Evidence-based restoration in the anthropocene – from acting with  
356 purpose to acting for impact. *Restoration Ecology*, 26, 201–205. <https://doi.org/10.1111/rec.12675>  
357 Dengler, J., Janišová, M., Török, P., & Wellstein, C. (2014). Biodiversity of Palaearctic grasslands: A  
358 synthesis. *Agriculture, Ecosystems & Environment*, 182, 1–14.  
359 <https://doi.org/10.1016/j.agee.2013.12.015>
- 360 Deutscher Wetterdienst. (2021). *Langjähriges Mittel der Wetterstation Metten 1981–2010*. [www.dwd.de](http://www.dwd.de)  
361 Dornbush, M. E., & Wilsey, B. J. (2010). Experimental manipulation of soil depth alters species richness  
362 and co-occurrence in restored tallgrass prairie. *Journal of Ecology*, 98, 117–125.  
363 <https://doi.org/10.1111/j.1365-2745.2009.01605.x>
- 364 Engst, K., Baasch, A., Erfmeier, A., Jandt, U., May, K., Schmiede, R., & Bruelheide, H. (2016).  
365 Functional community ecology meets restoration ecology: Assessing the restoration success of alluvial  
366 floodplain meadows with functional traits. *Journal of Applied Ecology*, 53, 751–764.  
367 <https://doi.org/10.1111/1365-2664.12623>
- 368 Freitag, M., Klaus, V. H., Bollinger, R., Hamer, U., Kleinebecker, T., Prati, D., Schäfer, D., & Hölzel, N.  
369 (2021). Restoration of plant diversity in permanent grassland by seeding: Assessing the limiting  
370 factors along land-use gradients. *Journal of Applied Ecology*, 58, 1681–1692.  
371 <https://doi.org/10.1111/1365-2664.13883>
- 372 Fukami, T. (2015). Historical contingency in community assembly: Integrating niches, species pools, and  
373 priority effects. *Annual Review of Ecology, Evolution, and Systematics*, 46, 1–23.  
374 <https://doi.org/10.1146/annurev-ecolsys-110411-160340>
- 375 Funk, J. L., Cleland, E. E., Suding, K. N., & Zavaleta, E. S. (2008). Restoration through reassembly: Plant  
376 traits and invasion resistance. *Trends in Ecology and Evolution*, 23, 695–703.  
377 <https://doi.org/10.1016/j.tree.2008.07.013>
- 378 Gabry, J., & Mahr, T. (2022). *bayesplot: Plotting for Bayesian models*. <https://mc-stan.org/bayesplot/>  
379 Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2019). Visualization in Bayesian  
380 workflow. *Journal of the Royal Statistical Society: Series A*, 182, 389–402.  
381 <https://doi.org/10.1111/rssa.12378>
- 382 Gelman, A., Goodrich, B., Gabry, J., & Vehtari, A. (2019). R-squared for Bayesian regression models.  
383 *The American Statistician*, 73, 307–309. <https://doi.org/10.1080/00031305.2018.1549100>
- 384 Grman, E., Bassett, T., & Brudvig, L. A. (2013). Confronting contingency in restoration: Management  
385 and site history determine outcomes of assembling prairies, but site characteristics and landscape  
386 context have little effect. *Journal of Applied Ecology*, 50, 1234–1243. <https://doi.org/10.1111/1365-2664.12135>  
387
- 388 Groves, A. M., Bauer, J. T., & Brudvig, L. A. (2020). Lasting signature of planting year weather on  
389 restored grasslands. *Scientific Reports*, 10, 5953. <https://doi.org/10.1038/s41598-020-62123-7>
- 390 Hari, V., Rakovec, O., Markonis, Y., Hanel, M., & Kumar, R. (2020). Increased future occurrences of the  
391 exceptional 2018–2019 Central European drought under global warming. *Scientific Reports*, 10,  
392 12207. <https://doi.org/10.1038/s41598-020-68872-9>
- 393 Hedberg, P., & Kotowski, W. (2010). New nature by sowing? The current state of species introduction in  
394 grassland restoration, and the road ahead. *Journal for Nature Conservation*, 18, 304–308.  
395 <https://doi.org/10.1016/j.jnc.2010.01.003>

- 396 Helm, A., Zobel, M., Moles, A. T., Szava-Kovats, R., & Pärtel, M. (2015). Characteristic and derived  
397 diversity: Implementing the species pool concept to quantify conservation condition of habitats.  
398 *Diversity and Distributions*, *21*, 711–721. <https://doi.org/10.1111/ddi.12285>
- 399 Holl, K. D., Luong, J. C., & Brancalion, P. H. S. (2022). Overcoming biotic homogenization in ecological  
400 restoration. *Trends in Ecology and Evolution*, *37*, 777–788. <https://doi.org/10.1016/j.tree.2022.05.002>
- 401 Husicka, A. (2003). *Vegetation, Ökologie und Erosionsfestigkeit von Grasnarben auf Flussdeichen am*  
402 *Beispiel der Rheindeiche in Nordrhein-Westfalen*. Dissertationes Botanicae 379. J. Cramer, Berlin–  
403 Stuttgart.
- 404 Janssen, J. A. M., Rodwell, J. S., García-Criado, M., Gubbay, S., Haynes, T., Nieto, A., Sanders, N. J.,  
405 Landucci, F., Loidi, J., Ssymank, A., Tahvanainen, T., Valderrabano, M., Acosta, A. T. R., Aronsson,  
406 M., Arts, G., Attore, F., Bergmeier, E., Bijlsma, R.-J., Bioret, F., ... Valachovič, M. (2016). *European*  
407 *red list of habitats: Part 2. Terrestrial and freshwater habitats*. Publication Office of the European  
408 Union, Luxembourg. <https://doi.org/10.2779/091372>
- 409 Jones, H. P., Jones, P. C., Barbier, E. B., Blackburn, R. C., Rey Benayas, J. M., Holl, K. D., McCrackin,  
410 M., Meli, P., Montoya, D., & Mateos, D. M. (2018). Restoration and repair of Earth's damaged  
411 ecosystems. *Proceedings of the Royal Society B: Biological Sciences*, *285*, 20172577.  
412 <https://doi.org/10.1098/rspb.2017.2577>
- 413 Kaulfuß, F., Rosbakh, S., & Reisch, C. (2022). Grassland restoration by local seed mixtures: new  
414 evidence from a practical 15-year restoration study. *Applied Vegetation Science*, *25*, e12652.  
415 <https://doi.org/10.1111/avsc.12652>
- 416 Kiehl, K., Kirmer, A., Donath, T. W., Rasran, L., & Hölzel, N. (2010). Species introduction in restoration  
417 projects. Evaluation of different techniques for the establishment of semi-natural grasslands in Central  
418 and Northwestern Europe. *Basic and Applied Ecology*, *11*, 285–299.  
419 <https://doi.org/10.1016/j.baae.2009.12.004>
- 420 Kleber-Lerchbaumer, U., Berger, C., & Veit, E. (2017). Gestaltung und Unterhaltung von Deichen und  
421 Deichschutzstreifen unter Anwendung der Bayerischen Kompensationsverordnung. Beispiel  
422 Donauausbau Straubing und Vilshofen. *KW Korrespondenz Wasserwirtschaft*, *10*, 596–606.
- 423 Kruschke, J. K. (2021). Bayesian analysis reporting guidelines. *Nature Human Behaviour*, *5*, 1282–1291.  
424 <https://doi.org/10.1038/s41562-021-01177-7>
- 425 Larson, J. E., Ebinger, K. R., & Suding, K. N. (2021). Water the odds? Spring rainfall and emergence-  
426 related seed traits drive plant recruitment. *Oikos*, *130*, 1665–1678. <https://doi.org/10.1111/oik.08638>
- 427 Laughlin, D. C. (2014). Applying trait-based models to achieve functional targets for theory-driven  
428 ecological restoration. *Ecology Letters*, *17*, 771–784. <https://doi.org/10.1111/ele.12288>
- 429 Legendre, P. (2019). A temporal beta-diversity index to identify sites that have changed in exceptional  
430 ways in spacetime surveys. *Ecology and Evolution*, *9*, 3500–3514. <https://doi.org/10.1002/ece3.4984>
- 431 Lemoine, N. P. (2019). Moving beyond noninformative priors: Why and how to choose weakly  
432 informative priors in Bayesian analyses. *Oikos*, *128*, 912–928. <https://doi.org/10.1111/oik.05985>
- 433 Liebrand, C. I. J. M., & Sykora, K. V. (1996). Restoration of semi-natural, species-rich grasslands on  
434 river dikes after reconstruction. *Ecological Engineering*, *7*, 315–326. [https://doi.org/10.1016/S0925-8574\(96\)00023-7](https://doi.org/10.1016/S0925-8574(96)00023-7)
- 435
- 436 Londo, G. (1976). The decimal scale for relevés of permanent quadrats. *Vegetatio*, *33*, 61–64.  
437 <https://doi.org/10.1007/BF00055300>
- 438 Merchant, T. K., Henn, J. J., Silva, I. de, Van Cleemput, E., & Suding, K. N. (2022). Four reasons why  
439 functional traits are not being used in restoration practice. *Restoration Ecology*, *31*, e13788.  
440 <https://doi.org/10.1111/rec.13788>
- 441 Mitchley, J., Jongepierová, I., & Fajmon, K. (2012). Regional seed mixtures for the re-creation of species-  
442 rich meadows in the White Carpathian Mountains: Results of a 10-yr experiment. *Applied Vegetation*  
443 *Science*, *15*, 253–263. <https://doi.org/10.1111/j.1654-109x.2012.01183.x>
- 444 Moreno-Mateos, D., Barbier, E. B., Jones, P. C., Jones, H. P., Aronson, J., López-López, J. A.,  
445 McCrackin, M. L., Meli, P., Montoya, D., & Rey-Benayas, J. M. (2017). Anthropogenic ecosystem

- 446 disturbance and the recovery debt. *Nature Communications*, 8, 14163.  
447 <https://doi.org/10.1038/ncomms14163>
- 448 Mouquet, N., Lagadeuc, Y., Devictor, V., Doyen, L., Duputié, A., Eveillard, D., Faure, D., Garnier, E.,  
449 Gimenez, O., Huneman, P., Jabot, F., Jarne, P., Joly, D., Julliard, R., Kéfi, S., Kergoat, G. J., Lavorel,  
450 S., Le Gall, L., Meslin, L., ... Loreau, M. (2015). Predictive ecology in a changing world. *Journal of*  
451 *Applied Ecology*, 52, 1293–1310. <https://doi.org/10.1111/1365-2664.12482>
- 452 Mucina, L., Bültmann, H., Dierßen, K., Theurillat, J.-P., Raus, T., Čarni, A., Šumberová, K., Willner, W.,  
453 Dengler, J., García, R. G., Chytrý, M., Hájek, M., Di Pietro, R., Iakushenko, D., Pallas, J., Daniëls, F.  
454 J. A., Bergmeier, E., Santos Guerra, A., Ermakov, N., ... Tichý, L. (2016). Vegetation of Europe:  
455 hierarchical floristic classification system of vascular plant, bryophyte, lichen, and algal communities.  
456 *Applied Vegetation Science*, 19, 3–264. <https://doi.org/10.1111/avsc.12257>
- 457 Myers, J. A., & Harms, K. E. (2009). Seed arrival, ecological filters, and plant species richness: A meta-  
458 analysis. *Ecology Letters*, 12, 1250–1260. <https://doi.org/10.1111/j.1461-0248.2009.01373.x>
- 459 Nerlekar, A. N., & Veldman, J. W. (2020). High plant diversity and slow assembly of old-growth  
460 grasslands. *Proceedings of the National Academy of Sciences*, 117, 18550–18556.  
461 <https://doi.org/10.1073/pnas.1922266117>
- 462 Oberdorfer, E. (1993). *Süddeutsche Pflanzengesellschaften. Teil II und III* (3rd ed.). Gustav Fischer,  
463 Stuttgart. ISBN 3334604357.
- 464 Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B.,  
465 Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B.,  
466 Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., ... Weedon, J. (2022). *vegan*:  
467 *Community ecology package*. <https://CRAN.R-project.org/package=vegan>
- 468 Orrock, J. L., Brudvig, L. A., Damschen, E. I., Mattingly, W. B., Cruz, J., Veldman, J. W., Hahn, P. G., &  
469 Larsen-Gray, A. L. (2023). Long-term, large-scale experiment reveals the effects of seed limitation,  
470 climate, and anthropogenic disturbance on restoration of plant communities in a biodiversity hotspot.  
471 *Proceedings of the National Academy of Sciences*, 120, e2201943119.  
472 <https://doi.org/10.1073/pnas.2201943119>
- 473 R Core Team. (2022). *R: A language and environment for statistical computing*. [https://www.R-](https://www.R-project.org/)  
474 [project.org/](https://www.R-project.org/)
- 475 Rydgren, K., Halvorsen, R., Töpper, J. P., Auestad, I., Hamre, L. N., Jongejans, E., & Sulavik, J. (2019).  
476 Advancing restoration ecology: A new approach to predict time to recovery. *Journal of Applied*  
477 *Ecology*, 56, 225–234. <https://doi.org/10.1111/1365-2664.13254>
- 478 Sabatini, F. M., Lenoir, J., Hattab, T., Arnst, E. A., Chytrý, M., Dengler, J., Ruffray, P. de, Hennekens, S.  
479 M., Jandt, U., Jansen, F., Jiménez-Alfaro, B., Kattge, J., Levesley, A., Pillar, V. D., Purschke, O.,  
480 Sandel, B., Sultana, F., Aavik, T., Ačić, S., ... Bates, A. (2021). sPlotOpen – an environmentally  
481 balanced, open-access, global dataset of vegetation plots. *Global Ecology and Biogeography*, 30,  
482 1740–1764. <https://doi.org/10.1111/geb.13346>
- 483 Stuble, K. L., Fick, S. E., & Young, T. P. (2017). Every restoration is unique: Testing year effects and site  
484 effects as drivers of initial restoration trajectories. *Journal of Applied Ecology*, 54, 1051–1057.  
485 <https://doi.org/10.1111/1365-2664.12861>
- 486 Suding, K. N., Gross, K. L., & Houseman, G. R. (2004). Alternative states and positive feedbacks in  
487 restoration ecology. *Trends in Ecology and Evolution*, 19, 46–53.  
488 <https://doi.org/10.1016/j.tree.2003.10.005>
- 489 Teixeira, L. H., Bauer, M., Moosner, M., & Kollmann, J. (2022). River dike grasslands can reconcile  
490 biodiversity and different ecosystem services to provide multifunctionality. *Basic and Applied*  
491 *Ecology*, 66, 22–30. <https://doi.org/10.1016/j.baae.2022.12.001>
- 492 Tölgyesi, C., Vadász, C., Kun, R., Csathó, A. I., Bátor, Z., Hábczyus, A., Erdős, L., & Török, P.  
493 (2021). Post-restoration grassland management overrides the effects of restoration methods in  
494 propagule-rich landscapes. *Ecological Applications*, 32, e02463. <https://doi.org/10.1002/eap.2463>
- 495 Török, P., Brudvig, L. A., Kollmann, J., Price, J. N., & Tóthmérész, B. (2021). The present and future of  
496 grassland restoration. *Restoration Ecology*, 29, e13378. <https://doi.org/10.1111/rec.13378>

- 497 Török, P., & Helm, A. (2017). Ecological theory provides strong support for habitat restoration.  
498 *Biological Conservation*, 206, 85–91. <https://doi.org/10.1016/j.biocon.2016.12.024>
- 499 United Nations. (2019). *United Nations decade on ecosystem restoration (2021–2030): Resolution*.  
500 *Adopted by the general assembly: A/RES/73/284*.  
501 [https://digitallibrary.un.org/record/3794317/files/A\\_RES\\_73\\_284-EN.pdf](https://digitallibrary.un.org/record/3794317/files/A_RES_73_284-EN.pdf)
- 502 Vannoppen, W., Poesen, J., Peeters, P., De Baets, S., & Vandevorode, B. (2016). Root properties of  
503 vegetation communities and their impact on the erosion resistance of river dikes. *Earth Surface*  
504 *Processes and Landforms*, 41, 2038–2046. <https://doi.org/10.1002/esp.3970>
- 505 Wainwright, C. E., Staples, T. L., Charles, L. S., Flanagan, T. C., Lai, H. R., Loy, X., Reynolds, V. A., &  
506 Mayfield, M. M. (2018). Links between community ecology theory and ecological restoration are on  
507 the rise. *Journal of Applied Ecology*, 55, 570–581. <https://doi.org/10.1111/1365-2664.12975>
- 508 Walker, K. J., Stevens, P. A., Stevens, D. P., Mountford, J. O., Manchester, S. J., & Pywell, R. F. (2004).  
509 The restoration and re-creation of species-rich lowland grassland on land formerly managed for  
510 intensive agriculture in the UK. *Biological Conservation*, 119, 1–18.  
511 <https://doi.org/10.1016/j.biocon.2003.10.020>
- 512 Wilsey, B. (2021). Restoration in the face of changing climate: Importance of persistence, priority effects,  
513 and species diversity. *Restoration Ecology*, 29, e13132. <https://doi.org/10.1111/rec.13132>
- 514 Zirbel, C. R., & Brudvig, L. A. (2020). Trait-environment interactions affect plant establishment success  
515 during restoration. *Ecology*, 101, e02971. <https://doi.org/10.1002/ecy.2971>
- 516



517 **Tables**

518 **Table 1**

519 Each plot received an individual set of twenty species with some restrictions to the number of species per functional group. The total species pool for hay  
520 meadows was 55 and for dry grassland 58. All individual seed mixtures are stored in Appendix A2.

521 **Table 1:**

Functional group	Species pool		Seed mixture	Total ratio	Ratio per species
	Hay meadow	Dry grassland			
	#	#	#	wt%	wt%
High grasses	6	5	3	25.7	8.6
Low grasses	8	8	4	34.3	8.6
Legumes	5	7	3	5.0	1.7
Herbs	34	36	9	30.0	3.3
Hemiparasites	2	2	1	5.0	5.0

522

523 **Table 2**

524 Characteristics of the substrates used for the sowing experiment on river dikes. Soil samples of the three substrates were analysed for the fraction <2 mm. The  
 525 soil texture was classified according to the ‘Bodenkundliche Kartieranleitung’ (Bundesanstalt für Geowissenschaften und Rohstoffe, 2005). The pH was  
 526 measured in CaCl<sub>2</sub> solution. Plant available phosphorus and potassium were measured in a calcium acetate-lactate extract and magnesium in a CaCl<sub>2</sub> extract.  
 527 For calculating CaCO<sub>3</sub>, a sub-sample was annealed at 550 °C and the measured C amount multiplied with 8.33. To calculate total N and the C/N ratio, a sub-  
 528 sample was incinerated at 1000 °C. Lt3 = medium clayey loam; Ls4 = strong sandy loam; Sl3 = medium loamy sand; Sl4 = strong loamy sand.

529 **Table 2:**

Exposition	Sand admixture	Skeleton (>2 mm)	Sand	Silt	Clay	Soil texture	pH	N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Mg <sup>2+</sup>	C/N	CaCO <sub>3</sub>
	vol%	vol%	wt%	wt%	wt%			wt%	mg 100 g <sup>-1</sup>	mg 100 g <sup>-1</sup>	mg 100 g <sup>-1</sup>		wt%
North	0	5	18	45	37	Lt3	7.4	0.35	4	6	27	8.9	12.1
	25	26	49	29	22	Ls4	7.4	0.24	4	5	25	9.0	8.8
	50	40	75	14	11	Sl3	7.5	0.11	3	4	17	9.5	5.3
South	0	9	18	45	37	Lt3	7.3	0.37	6	7	28	8.8	12.5
	25	26	59	23	18	Ls4	7.4	0.19	3	5	23	9.2	7.3
	50	44	71	18	13	Sl4	7.5	0.13	4	5	16	9.5	7.3

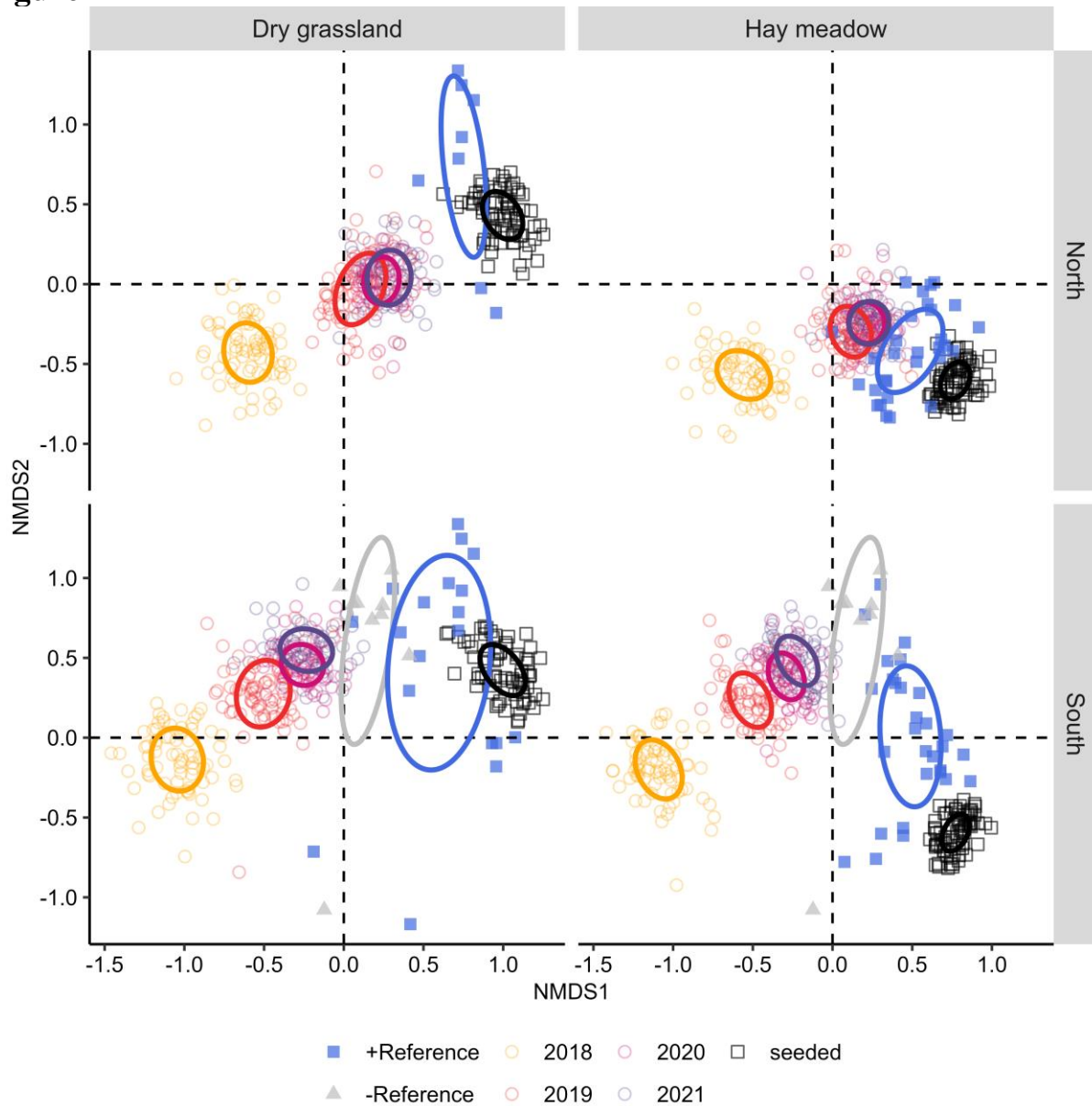




539 depth, seed density, and seed mixture types H and D (hay meadows, dry grasslands). The western half of  
540 a block had a shallow substrate depth and within this, half of the substrates had different sand admixtures.  
541 The photo on the bottom shows the northern slope of one block in 2021, four years after sowing (photo:  
542 Markus Bauer).

543

544 **Figure 2**



545

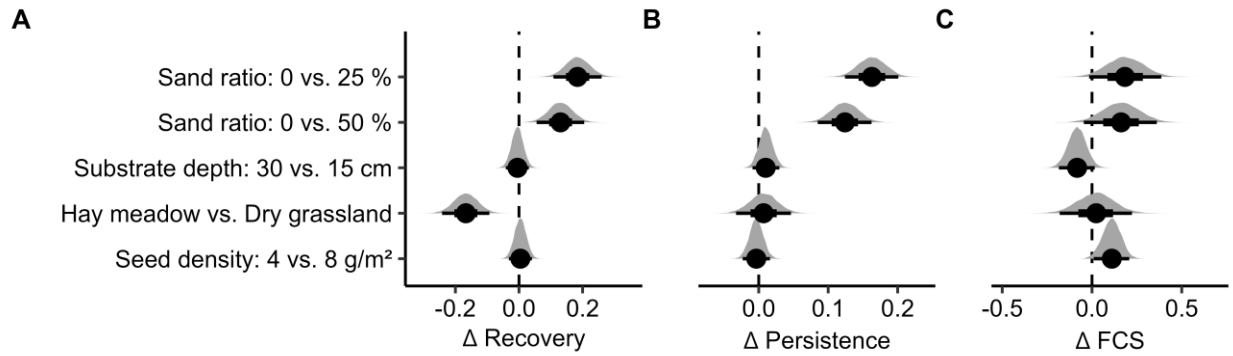
546 **Figure 2:**

547 The species composition of sown experimental plots on a river dike over time and in comparison with  
548 reference sites and the seed mixtures. Both expositions and both seed mixture types are shown in separate  
549 panels. The NMDS was based on the Sørensen dissimilarity and data of 288 plots observed over four  
550 years after sowing in 2018 (circles). These experimental plots were compared with the seed mixtures  
551 (black squares) and 98 positive and negative reference plots (filled symbols) from older dike grasslands in

552 the surroundings (Bauer et al., 2023a), and six plots from sPlotOpen (Sabatini et al., 2021). The ellipses  
553 show the standard error of the groups. 2D-stress: 0.21.

554

555 **Figure 3**



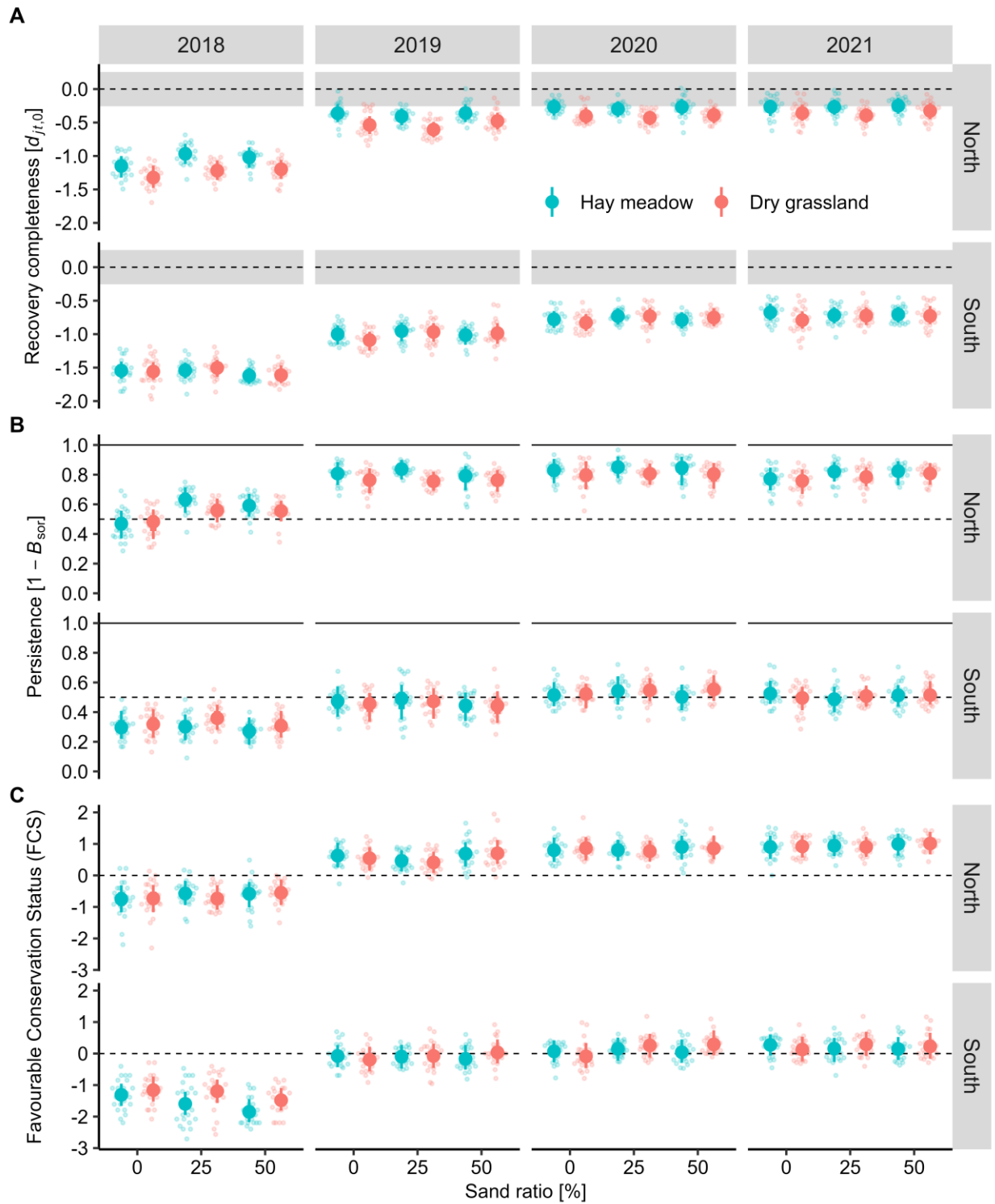
556

557 **Figure 3:**

558 Effects of treatments on the development of sown grassland communities at a river dike. The posterior  
559 density distributions (grey) are calculated over all four surveyed years and both expositions. Shown are  
560 the medians, 66% and 95% credible intervals, which were derived from a Bayesian linear mixed-effects  
561 model (BLMM). Shown are (A) the recovery completeness compared to reference sites, (B) the  
562 persistence of sown species, and (C) the Favourable Conservation Status (FCS). The FCS is the ratio of  
563 target species to non-target species. Note that the zero lines indicate that both levels have equal values.  
564 This means, e.g., that hay meadows are closer to their reference than dry grasslands (A).

565

566 **Figure 4**



567

568 **Figure 4:**

569 The development of grassland communities at a river dike over four years after sowing. The plots had  
570 substrates with different sand admixtures and were sown with two different seed mixture types. Three  
571 indices are evaluated. (A) Recovery completeness ( $d_{ji,0}$ ): the zero lines indicate the mean position of the  
572 reference sites for each habitat type on the NMDS axis 1 (Figure 2). The grey area marks the standard  
573 deviation of the position of the reference sites (Figure 2). (B) Persistence of sown species: losses  
574 component of the temporal beta-diversity index ( $1 - B_{sor}$ ). (C) Favourable Conservation Status (FCS): the  
575 zero line indicates that target and non-target species are balanced. Positive values indicate that there are  
576 more target species. Shown are the medians and 95% credible intervals of the posterior distributions,  
577 which were derived from a Bayesian linear mixed-effects model (BLMM).

578

## 579 Session Info

```
580 ## R version 4.2.2 (2022-10-31 ucrt)
581 ## Platform: x86_64-w64-mingw32/x64 (64-bit)
582 ## Running under: Windows 10 x64 (build 22621)
583 ##
584 ## Matrix products: default
585 ##
586 ## locale:
587 ## [1] LC_COLLATE=German_Germany.utf8 LC_CTYPE=German_Germany.utf8
588 ## [3] LC_MONETARY=German_Germany.utf8 LC_NUMERIC=C
589 ## [5] LC_TIME=German_Germany.utf8
590 ##
591 ## attached base packages:
592 ## [1] stats      graphics  grDevices datasets  utils      methods    base
593 ##
594 ## other attached packages:
595 ## [1] flextable_0.8.6 lubridate_1.9.2 forcats_1.0.0 stringr_1.5.0
596 ## [5] dplyr_1.1.0      purrr_1.0.1     readr_2.1.4   tidyr_1.3.0
597 ## [9] tibble_3.1.8     ggplot2_3.4.1  tidyverse_2.0.0 officer_0.6.0
598 ## [13] officedown_0.3.0 knitr_1.42      here_1.0.1
599 ##
600 ## loaded via a namespace (and not attached):
601 ## [1] bit64_4.0.5          vroom_1.6.1          jsonlite_1.8.4
602 ## [4] shiny_1.7.4          askpass_1.1          fontLiberation_0.1.0
603 ## [7] renv_0.16.0          yaml_2.3.7           gdttools_0.3.1
604 ## [10] pillar_1.8.1         glue_1.6.2           uuid_1.1-0
605 ## [13] digest_0.6.31       promises_1.2.0.1    colorspace_2.1-0
606 ## [16] htmltools_0.5.4     httpuv_1.6.9         gfonts_0.2.0
607 ## [19] fontBitstreamVera_0.1.1 pkgconfig_2.0.3     httpcode_0.3.0
608 ## [22] xtable_1.8-4         scales_1.2.1         later_1.3.0
609 ## [25] fontquiver_0.2.1    tzdb_0.3.0           timechange_0.2.0
610 ## [28] openssl_2.0.5       generics_0.1.3       ellipsis_0.3.2
611 ## [31] cachem_1.0.7         withr_2.5.0          cli_3.6.0
612 ## [34] magrittr_2.0.3      crayon_1.5.2         mime_0.12
613 ## [37] memoise_2.0.1       evaluate_0.20        fansi_1.0.4
614 ## [40] xml2_1.3.3          textshaping_0.3.6   tools_4.2.2
615 ## [43] data.table_1.14.8   hms_1.1.2            lifecycle_1.0.3
616 ## [46] munsell_0.5.0       zip_2.2.2            compiler_4.2.2
617 ## [49] systemfonts_1.0.4  rlang_1.0.6          grid_4.2.2
618 ## [52] rstudioapi_0.14    rmarkdown_2.20      gtable_0.3.1
619 ## [55] curl_5.0.0         R6_2.5.1            rvg_0.3.2
620 ## [58] fastmap_1.1.1      bit_4.0.5           utf8_1.2.3
621 ## [61] rprojroot_2.0.3    ragg_1.2.5          stringi_1.7.12
622 ## [64] parallel_4.2.2     crul_1.3            Rcpp_1.0.10
623 ## [67] png_0.1-8          vctrs_0.5.2         tidyselect_1.2.0
624 ## [70] xfun_0.37
```