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RESEARCH ARTICLE

Evaluating CAP wildflower strips: High-quality seed mixtures significantly improve plant diversity and related pollen and nectar resources

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Abstract

1. Flower strips are a fundamental part of agri-environment schemes (AESs) introduced by the European Union to counteract the loss of biodiversity and related ecosystem services in agricultural landscapes. Although vegetation composition of the strips is essential for most fauna groups, comprehensive studies analysing vegetation development and influencing factors are rare.
2. From 2017 to 2019, we investigated the vegetation composition of 40 perennial wildflower strips (WFSs) implemented in 2015 or 2016, and 20 cereal fields without WFS across Saxony-Anhalt, Germany. We analysed environmental factors on plot (cover of grasses, shading, soil fertility) and four landscape-scale levels (habitat diversity, proportion of WFS and open habitats). The provision of nectar and pollen resources was estimated by the newly developed Pollinator Feeding Index (PFI). All strips had been implemented by farmers as AES with species-rich seed mixtures comprising 30 native forbs.
3. In all study years, forb species richness, cover and related nectar and pollen supply were much higher on WFSs than on controls, confirming the effectiveness of this AES. Although sown native forbs contributed the most to the high PFI values, spontaneously established forbs expanded the total range of species considerably, especially in winter and spring. While sown forb communities remained similar over time, spontaneous forbs showed a higher species turnover. Altogether, shading and grass cover had the greatest negative effect on the performance of the sown forbs. Landscape variables had only minor effects and were inconsistent in their importance across scale levels and years.
4. *Synthesis and applications*. Successfully established perennial wildflower strips (WFSs) sown with species-rich native seed mixtures provided a forb-rich and diverse vegetation throughout the AES funding period of 5 years. By supplying feeding resources for pollinators under various landscape situations, WFSs have significant potential to promote farmland biodiversity and related ecosystem

services. We recommend the mandatory use of species-rich wildflower mixtures for perennial flower strips and to avoid their creation in heavily shaded field edges. Advisory services for farmers are necessary to prevent failures in WFS implementation and management and to improve their ecological effectiveness.

KEYWORDS
agri-environment schemes, farmland biodiversity, flower strip effectiveness, landscape context, native plant species, perennial wildflower strips, Pollinator Feeding Index, vegetation monitoring

1 | INTRODUCTION

In recent decades, intensification has led to a massive biodiversity loss in agricultural landscapes throughout Europe (Seibold et al., 2019) due to effective weed control, field enlargements, short crop rotation as well as the ploughing of grassland (Baessler & Klotz, 2006; Meyer et al., 2013). The remaining plant communities are often species poor, dominated by highly competitive grasses and nitrophilous ruderals and are often isolated. The reduced availability of flowering plants as resources of pollen and nectar in agricultural landscapes has led to a significant decline in pollinator diversity (Biesmeijer et al., 2006) affecting important ecosystem services such as pollinator performance (Clough et al., 2014). The integration of agri-environment schemes (AESs) in the common agricultural policy (CAP) is an attempt to counteract this negative trend (Scheper et al., 2013). Flower strips are among the most commonly applied AES in Germany and aim to enhance biodiversity by providing shelter as well as food resources for different animal taxa, for example pollinators (Ouvrard et al., 2018). Perennial flower strips are sown on a part of the arable field once at the beginning of the funding period of 5 years. Farmers receive subsidies to compensate for yield loss and maintenance costs.

Although vegetation is fundamental for many animal species groups, it was often not or only sporadically evaluated in mainly faunistically focused studies on flower strips (Zingg et al., 2019, but see Schmidt et al., 2022). To sustainably improve flower strip performance, the design of AESs and thus their ecological effectiveness, it is necessary to evaluate their quality over several years to understand what determines their failure or success (Albrecht et al., 2021). Existing studies that focus exclusively on vegetation often refer to mixtures containing mainly cultivar species or to species-poor (<15 species) wild plant mixtures (Delphia et al., 2019; Piqueray et al., 2019; Uyttenbroeck et al., 2015). Since many insect species depend on a specific plant species or genus (Potts et al., 2010), perennial wildflower strips (WFSs), sown with species-rich native seed mixtures from regional seed propagations, are expected to better provide the desired diversity of nectar and pollen (Wood et al., 2017). However, to our knowledge, floristic evaluations of such WFSs and their development over several years are scarce (Pywell et al., 2011). A previous study showed that high diversity seed mixtures with regionally typical native plants ensured high species diversity and cover of native perennial wildflowers within the AES funding period of 5 years and beyond (Schmidt et al., 2020). However, that study was conducted only on small experimental plots and it is unclear if such an approach will provide the desired functional diversity in agricultural practice (Lepŝ et al., 2007).

To date, factors influencing vegetation composition of WFSs over time have rarely been investigated (but see Piqueray et al., 2019). Spontaneously establishing species from the soil seed bank or immigrating from adjacent structures can affect species assemblage and diversity in two ways. Spontaneous forbs may significantly increase plant species richness and the flowering aspect, and expand the food supply. Dominance of spontaneous grasses, however, may jeopardise success. With increasing soil fertility, vegetation stands often become taller and denser with increased competition (Piqueray et al., 2021), especially on shaded sites. Contrary to general recommendations, farmers often place flower strips on heavily shaded, north-exposed forest edges or in areas with already existing high weed pressure because the yield would be low there anyway. Whether measures designed for animal taxa adapted to predominantly open and sunny agricultural landscape can develop as desired under these conditions is questionable.

In addition, the evaluation of conservation actions should not only consider local field conditions, but also the landscape context (Kleijn et al., 2011), as other studies verified, for example, the importance of habitat connectivity (Brudvig et al., 2009). A high amount of semi-natural habitats of open landscapes like grasslands or a generally high habitat diversity in the vicinity may increase overall plant species richness by providing a higher local species pool (Moser et al., 2002), or they decrease the establishment success due to a higher immigration of competitive weeds. Moreover, these effects could vary depending on local site conditions, for example soil fertility. Since the participation of farmers in AES programmes and thus the spatial distribution of WFSs varies greatly at the landscape level, similar landscape effects could possibly appear by considering the area under flower strip management. As landscape effects can change with increasing distance, multiple scales have to be considered.

To address these questions, we investigated the vegetation on 40 WFSs implemented in agricultural practice and spread across the federal state of Saxony-Anhalt, Germany, and 20 cereal crop fields without WFS as control, from 2017 to 2019. Environmental parameters were included in our analyses, to evaluate the effects of local site conditions, landscape structure and WFS proportion on vegetation composition of WFSs in a multi-scale evaluation. To test for changes in forb communities through time, we quantified temporal beta diversity and partitioned components. Since the primary goal of WFSs is to promote faunal diversity, we developed an index to estimate their benefits for pollinators with regard to nectar and pollen resources. Research questions were:

1. How do perennial WFSs increase plant diversity compared to arable fields? Does this effect persist until the fourth/fifth year after implementation?
2. What proportion of the vegetation composition is represented by sown forbs, spontaneous forbs and grasses, and how do communities change over time? Which plot (grass cover, shading, soil fertility) or landscape-level factors (proportion of WFS or non-intensively used open habitats, habitat diversity) affect the number and cover of sown forbs, spontaneous forbs and grasses?
3. Do WFSs increase pollen and nectar resources according to the developed PFI? Which role do sown versus spontaneous forbs play?

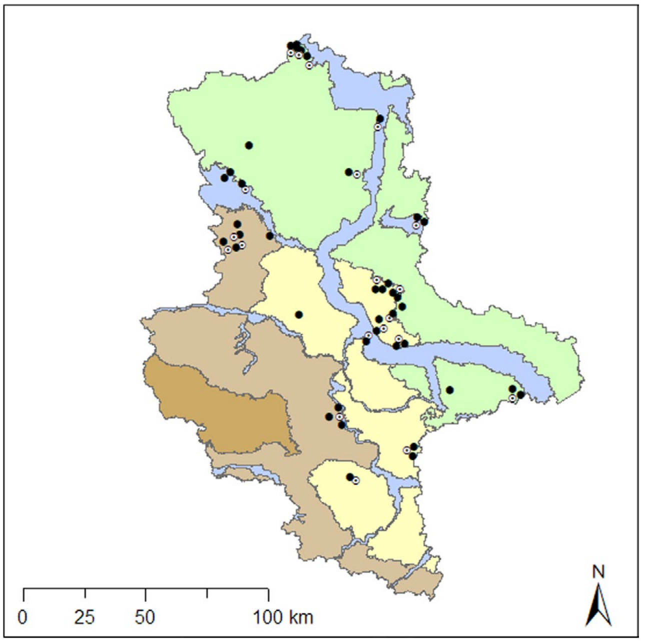


FIGURE 1 Location of the study plots in Saxony-Anhalt, central Germany (Schmidt et al., 2022, modified): wildflower strip plots (black dots) and controls (two-coloured dots). Filled in colour: landscape units (simplified based on Reichhoff et al., 2001, data basis: State Office for Environmental Protection Saxony-Anhalt)

2 | MATERIALS AND METHODS

2.1 | Study area

The study was conducted in the federal state of Saxony-Anhalt, Germany. The climate is rather dry with an annual mean temperature of 9.3 degree Celsius and annual precipitation of 579 mm (long-term mean 1981–2010, German Meteorological Service, 2020). Sandier soils such as brown earth dominate in the north and east of the federal state, interrupted by loamy gleys and fen soils along rivers and in lowlands. A loess belt with fertile chernozem soils can be found in the central part of the state. More than 60% of Saxony-Anhalt is used as arable land, mainly for cereal, rape and maize cultivation. The average field size in the study areas was 18 ± 22.3 ha (mean ± *SD*).

2.2 | Study design and wildflower strip specification

Study sites with WFS ($n = 40$) were randomly chosen from 272 WFSs with a minimum length of 200 m that were established in 2015 or 2016 by farmers in agricultural practice on arable fields under the Saxony-Anhalt AES directive for the 5-year funding period (Fenchel et al., 2015; Figure 1). Selected WFS sites varied along a gradient regarding landscape heterogeneity and area under WFS management in the surroundings. As controls, we selected cereal crop fields lacking WFSs ($n = 20$). Controls were stratified-randomly selected on cereal crop fields from the same landscape units at a minimum distance of 1,000 m. WFSs and controls were always selected in a 2:1 ratio per landscape unit (Figure 1; Figure S1). The uneven spatial distribution of the study plots corresponds to a regionally varying participation of farmers in the AES.

At the time of the first data collection in 2017, WFSs were in their second/third year, and at the end of the observation period in 2019 in their fourth/fifth year. Seed mixtures, obligatorily used for AESs within the CAP funding period 2014–2020, contained 30 native forbs from a certified regional seed propagation (parent seeds taken from the wild with proof of provenance, see Mainz & Wieden, 2019) and cost about 500 € per hectare, with a sowing rate of 0.4–0.5 g/m^2. The investigated WFSs were sown with two different seed mixtures due to varying soil conditions (loess-loam, $n = 14$ or sand-loam, $n = 26$), containing 18 identical and 12 different species. Management by farmers was on a voluntary basis; fertiliser and pesticide application was forbidden (Fenchel et al., 2015). For further information about the seed mixtures and WFS regulations, see Appendix S1.

2.3 | Vegetation surveys

On each of the selected WFSs and control cereal fields, the presence of all vascular plant species was recorded along a 5 m × 200 m transect at the field edge and within 2 m to the adjacent landscape structure (see Figure S2). Species per cent cover was estimated in four permanently marked 2 m × 2 m plots per site within the 1,000 m^2 transect. To avoid edge effects, each quadrat was systematically placed in the centre of a 5 m × 50 m section. Permanent plots were recorded each year from 2017 to 2019 once between mid-May and the end of June. Nomenclature follows Jäger (2017). Vegetation surveys were granted by the Ministry of Environment, Agriculture and Energy Saxony-Anhalt and did not require ethical approval.

For each year and plot, we calculated total plant species richness, the number and cumulative cover of sown and spontaneous forbs and grasses. Values regarding species richness were derived from the 1,000 m^2 transect. To calculate the cumulative cover of sown/spontaneous forbs and grasses, the cover of the respective species per permanent plot was summed and then averaged per WFS site to avoid pseudo-replication.

2.4 | Environmental parameters and Pollinator Feeding Index

The calculation of shading was based on the assumption that the sun rises exactly in the east and sets in the west (Table 1). In our study, 50% of WFSs received sunlight almost all day, while 50% were shaded. Since the proportion of area under WFS management and of non-intensively used open habitats varied greatly in the vicinity of the study sites, we included both as metric landscape variables in our analyses. Habitat types were mapped within a 1,000 m radius around each vegetation transect using an adjusted standard habitat mapping key of Saxony-Anhalt (Schmidt et al., 2022 on the basis of Peterson & Langner, 1992). The mapped data were digitalised, and habitat proportions (WFS, open habitats) and habitat diversity were calculated with four radii (250, 500, 750 and 1,000 m) around the centre of the vegetation transect using ESRI ArcGIS 10.4.1. In order to distinguish between the effects of environmental variables per year and per sown and spontaneous forbs, the categorical factors 'year' and 'status' were included (Table 1).

We developed a Pollinator Feeding Index (PFI), which was calculated per plot for sown and spontaneously established forb species separately, taking into account pollen (P) and nectar production (N) as well as flowering period (number of flowering months; Jäger, 2017) and the respective cover (relevé data). The PFI factor corresponds to the species-specific coefficient by which the cover of a species is multiplied (Table S1).

$$\mathrm{PFI_{plot}} = \sum_{i=1}^{n} \left(P_i + N_i\right) \times \mathrm{flowering\ period}_i \times \mathrm{cover}_i$$

Depending on nectar and pollen production, species were separately divided into classes between none (=0) and very high productivity (=4; Pritsch, 2007). Grass species were not taken into account, as their pollen seems to be used only in exceptional cases. Finally, the $\mathrm{PFI_{plot}}$ values were averaged per site. The PFI was designed to better assess the significance of a site as a food resource for pollinators from relevé data by taking into account plant biological and ecological parameters in the calculation.

2.5 | Statistical analysis

Statistical analyses were performed in R version 4.0.2 (R Core Team, 2020) and figures created using ggplot2 3.3.2 (Wickham, 2016).

2.5.1 | Comparison of wildflower strips and control crop fields

Mann–Whitney *U* tests (stats 4.0.3) were used to analyse statistical differences in total species richness and PFI between WFSs and controls.

TABLE 1 Description of explanatory variables used in mixed models for analysing the potential effects on species richness and cover of forbs and cover of grasses on WFSs. Variables were generated for plot (vegetation survey plot) or landscape level, separately analysing the 250, 500, 750 and 1,000 m radii

Level	Explanatory variables	Description	WFS: Mean ± *SD* (*n* =40)
Plot	Soil fertility (continuous)	Value for the evaluation of the yield capacity of agricultural soils (Law on the valuation of agricultural soils in Germany, 2007). It ranges from very low (=0) to very high productivity (=100)	43.4 ± 20.6
	Shading (continuous)	Proportion of the WFSs that is shaded during the day due to high adjacent woody structures. It ranges from full sun exposure (0% = 0°) to full shading (100% = 180°).	30.1 ± 37.0%
	C. grasses (continuous)	Cumulative cover of grasses (only forb models)	29.9 ± 22.9%
Landscape	% WFS (continuous)	Proportion of WFS	1.1 ± 1.0%
	% Open habitats (continuous)	Proportion of non-intensively used open habitats, for example grassland, other AES such as fallows, tall herbaceous vegetation	11.5 ± 9.4%
	Habitat diversity (continuous)	Shannon's diversity index, calculated of different codes from the habitat mapping key	2.0 ± 0.5
	Year (categorical)	Study years: 2017, 2018, 2019	—
	Status (categorical)	Sown or spontaneous forbs (only forb models)	—

2.5.2 | Vegetation composition of wildflower strips and influencing factors

Generalized linear mixed models (GLMM) or linear mixed models (LMM) were fitted to evaluate whether forb species richness (sown and spontaneous forbs, count data, GLMM with negative binomial error distribution to account for overdispersion), forb cover (sown and spontaneous forbs, LMM) or cover of grasses (LMM) on WFSs were affected by environmental variables or years (Table 1), using lme4 1.1-21 (Bates et al., 2015) and MuMIn 1.43.17 for multi-model selection and averaging (Bartoń, 2020). Since percentage cover data are strictly bounded but not binomial, we logit-transformed the cover data prior to statistical analysis (Warton & Hui, 2011) to achieve normally distributed residuals and avoid heteroscedasticity. Assumptions were checked graphically as recommended by Smith et al. (2009). We modelled the effects of six environmental variables at plot and landscape level (Table 1), separately evaluating the landscape effect at four spatial scales (250, 500, 750 and 1,000 m). By selecting those environmental variables, we avoided strong inter-correlations among the predictors ($|r| > 0.6$, Pearson's correlation analysis, Appendix S2). Moreover, we included all two-way interactions between plot-level and plot-level variables and between plot-level and landscape-level variables (except for cover of grasses, which was analysed as a separate response variable), and the interactions between the proportion of WFS and the other landscape-level variables. Possible dependence in the data due to spatially close locations, repeated measurements in the same permanent WFS plots and usage of different seed mixtures was controlled by incorporating landscape units, WFS site and mixture as random variables in the models. Multi-model selection was based on Akaike information criterion (AIC) and relative importance values of all predictors were calculated using AIC weights from all analysed models. For model averaging, we selected all models with $\Delta AIC < 4$ compared to the best model according to AIC.

Temporal beta diversity was analysed to assess the variation in forb communities through the observation period. Specifically, we calculated total dissimilarity of sown and spontaneous forbs based on the Sørensen index and its nestedness and turnover components, using betapart 1.5.4 (Baselga & Orme, 2012). Mann–Whitney *U* tests (stats 4.0.3) were used to analyse statistical differences in beta diversity between sown and spontaneous forbs.

3 | RESULTS

3.1 | Comparison of wildflower strips and control crop fields

In each of the three study years, plant species richness and cover of non-crop species were considerably higher on WFSs than on controls ($p < 0.001$, Mann–Whitney *U* test). On controls, 8.3 ± 1.5 (mean $\pm$ *SE*) spontaneous species (forbs and grasses) both with a very low cover occurred in addition to the crop (Figure 2), while total plant species richness on WFSs was 61.5 ± 1.0 (mean $\pm$ *SE*) per 1,000 m².

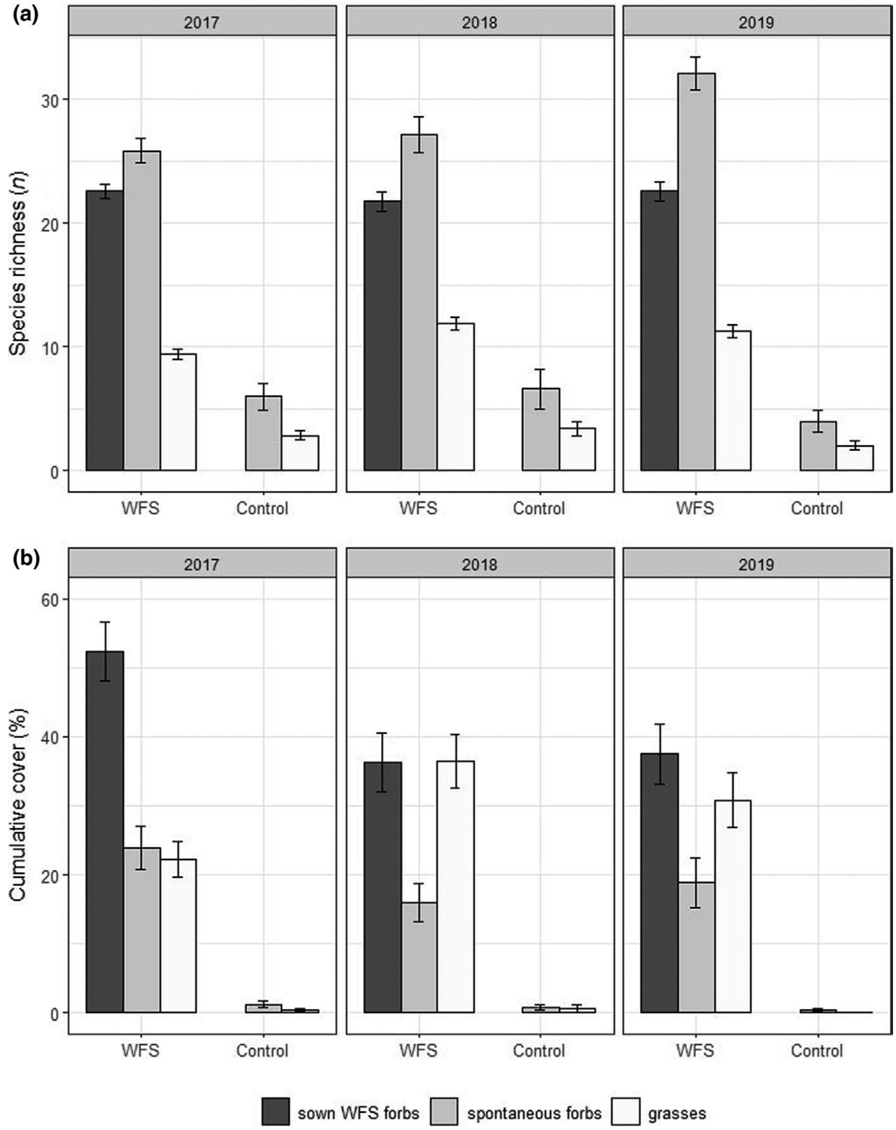
3.2 | Vegetation composition of wildflower strips and influencing factors

On WFSs, most plant species were forbs (Figure 2a; Table S1). The species richness of sown and spontaneously established forbs was similar in the first study year. Contrary to the constant number of sown forb species, the species richness of spontaneous forbs increased significantly over the study years (Figures 2a and 3; Appendix S3). Of the 30 forb species sown, 22 species per 1,000 m² were found continuously in each of the survey years, resulting in an establishment rate of 73%. *Achillea millefolium*, *Centaurea jacea*, *Daucus carota*, *Lotus corniculatus* and *Silene vulgaris* had the highest frequency as they appeared on most WFSs in all years. Each of the sown forbs established on at least two WFSs and only three (sand-loam mixture) and five forbs (loess-loam mixture) were not detected on at least 50% of the WFSs in any of the 3 years. Mean temporal beta diversity of sown forb communities was <0.3 in both annual comparisons (Figure 4). Species turnover and nestedness contributed nearly balanced to dissimilarity. In addition to sown forbs, 28.4 ± 0.8 (mean $\pm$ *SD*) forb species established spontaneously with *Fallopia convolvulus* and *Tripleurospermum inodorum* being the most frequent species. Temporal beta diversity of spontaneous forb communities decreased over time, but was significantly higher than values for sown forbs (Mann–Whitney *U* test, $p < 0.001$). On average, turnover represented approximately 70% of spontaneous forb temporal beta diversity between 2017 and 2018, and was lower between 2018 and 2019, but still higher than nestedness. At all scale levels, forb species richness decreased with increased shading, with sown forbs being more affected, as shown by the significant interaction (Figure 5a–c). Soil fertility was important in most models, but only significant as interaction with status at two scale levels. Landscape-level factors did not show significant effects in the averaged model estimates and were inconsistent in their importance across scale levels and years (Figure S3).

Forbs had the largest share of total plant cover on WFSs in all study years on most sites. The cover of sown forbs was significantly higher than the cover of spontaneous forbs, but decreased over the study period (Figure 2b; Appendix S3). Forb cover was negatively affected by the cover of grasses (Figure 3). While the cover of the sown forbs decreased strongly with more shading (Figure 5e), the cover of the spontaneous forbs remained largely stable (Figure S4), as indicated by the significant interaction. Soil fertility, the proportions of open habitats and WFS and the interaction status × cover of grasses had a higher relative importance (Figure S5), but did not show significant effects in the full averaged models. The 13 species with the highest cover of all forbs over all study sites and years were sown species, with *A. millefolium*, *Galium album*, *D. carota*, *Leucanthemum vulgare* and *C. jacea* being the most abundant.

In the first study year, grass cover was similar to the cover of spontaneous forbs, but lower than the cover of sown forbs (Figure 2b). Grass cover increased and peaked in 2018, being higher on shadier and more productive sites (Figure 3; Appendix S3; Figure S6). The proportion of open habitats and habitat diversity had a higher predictor importance in models explaining grass cover at all scale levels, with a significant interaction year × habitat diversity at the 250 m scale level (Figure S7). Especially WFSs with a high cover of

FIGURE 2 Mean species richness per 1,000 m^2 (a) and cumulative cover (b) ($\pm SE$) of sown forb species, spontaneous forb species and grasses on wildflower strips (WFS) compared to controls in 2017, 2018 and 2019



grasses in the first year of the study also showed high grass cover in the following years (2017 ~ 2018: $r_{\text{Pearson}} = 0.44$; 2018 ~ 2019: $r_{\text{Pearson}} = 0.68$, see Figure S8). The grass species *Holcus lanatus*, *Bromus sterilis*, *Elymus repens* and *Poa trivialis* were by far the most common species causing undesired monodominance (Table S2).

3.3 | Expected benefits for pollinators (Pollinator Feeding Index)

According to the calculated PFI, the availability of feeding resources was significantly higher on WFSs than on controls, where nearly no pollen and nectar-producing forbs occurred ($p < 0.001$, Mann–Whitney *U* test, Figure 6). On WFSs, pollen and nectar were mainly supplied by sown forbs, which provided more than twice as much from June to October than spontaneously established forbs (Figure 7). From November to May, spontaneous forbs provided most of the pollen and nectar, albeit at mainly low values. The spontaneously established *Capsella bursa-pastoris*, *Taraxacum* sect. *Ruderalia* and *Veronica persica* had the highest PFI factors of all detected species. The sown *L. vulgare*, *D. carota*, *A. millefolium*, *C. jacea* and *Trifolium pratense* were most important for pollinators according to the PFI as they all have a generally high nectar and pollen production, and were found in high cover on the WFSs (see Table S1 for total forb species list and corresponding PFI factors and mean PFI values). The PFI decreased from 2017 to 2018/2019, with sown forbs declining less than spontaneous forbs.

4 | DISCUSSION

4.1 | Comparison of wildflower strips and control crop fields

In the last 3 years of the 5-year AES funding period, total plant species richness on WFSs was more than six times higher than on control cereal fields. This confirms the effectiveness of perennial WFSs to enhance plant diversity in agricultural landscapes (Balzan et al., 2014). Although the permanent plots were located at field edges, which are usually more species-rich than the interior (Bellanger et al., 2012), the majority of controls had less than 10 species per 1,000 m²,

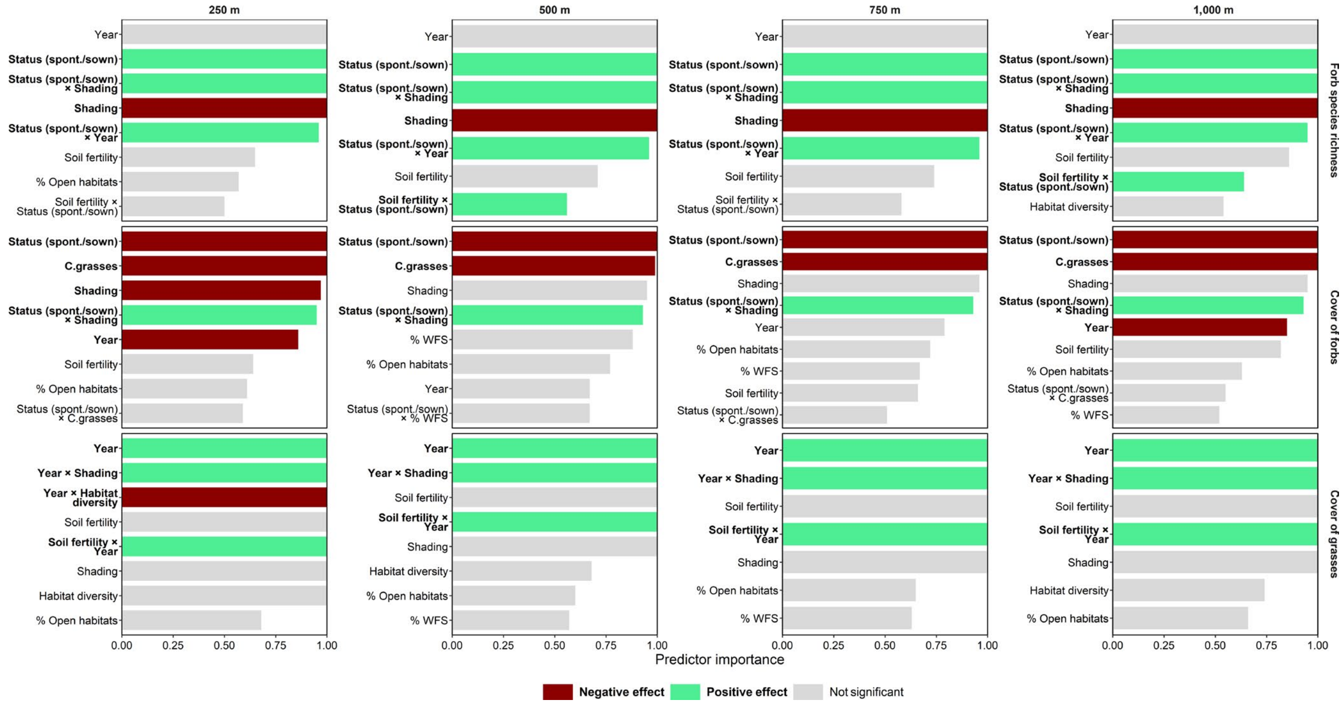


FIGURE 3 Relative importance of explanatory variables and two-way interactions in the multi-model procedures for the species richness of forbs per 1,000 m^2, cumulative cover of forbs and cumulative cover of grasses on WFSs from 2017 to 2019 at scales from 250 to 1,000 m. The figure includes all variables with importance values of 0.5 and higher. For abbreviations, see Table 1. Predictors marked in bold had significant estimates ($p < 0.05$) in the full averaged models. Reference levels: year: 2017, status: sown

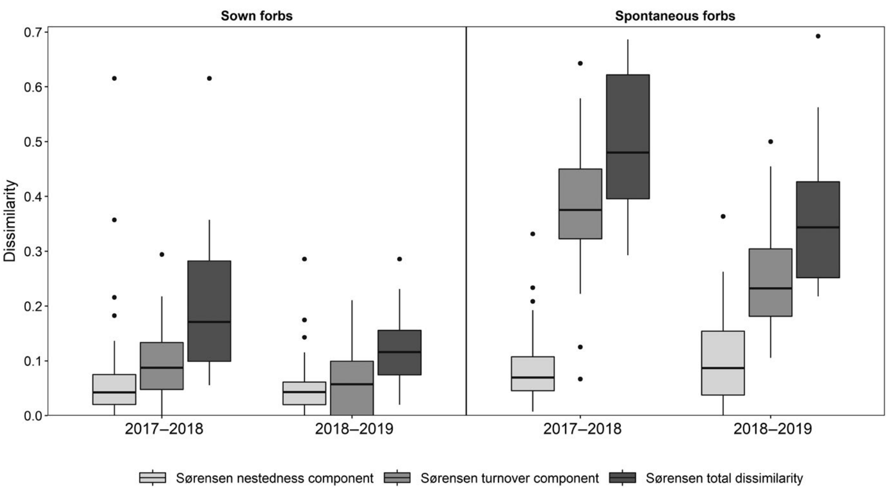


FIGURE 4 Temporal beta diversity and its turnover and nestedness resultant components per 1,000 m^2 of sown and spontaneous forb species communities, calculated as mean pairwise-site Sørensen dissimilarity between years

validating the negative effects of intensive agriculture found by Meyer et al. (2013) and Baessler and Klotz (2006). Within the field, plant diversity is probably even lower, highlighting the indispensable need for biodiversity-enhancing measures in agricultural landscapes.

4.2 | Vegetation composition of wildflower strips and influencing factors

With an average 73%, the mean establishment rate of sown wildflowers in WFSs implemented by farmers was similar to experimental conditions in a previous study (Schmidt et al., 2020), and remained stable over all study years. The very low beta diversity further indicated a high level of similarity and persistence for sown forb communities on most sites from the second/third to the fourth/fifth year of establishment. None of the sown species of the two investigated mixtures completely failed to establish. Which sown species were actually present on a WFS varied greatly between sites. The reasons for such spatial variability are difficult to determine and are not always only linked to site conditions (Lepŝ et al., 2007). Inter- and intraspecific competition can also play a role (Wassmuth et al., 2009). However, in terms of risk diversification ('insurance effect'), our species-rich mixtures were suitable for guaranteeing a good performance of the WFSs over the AES funding period.

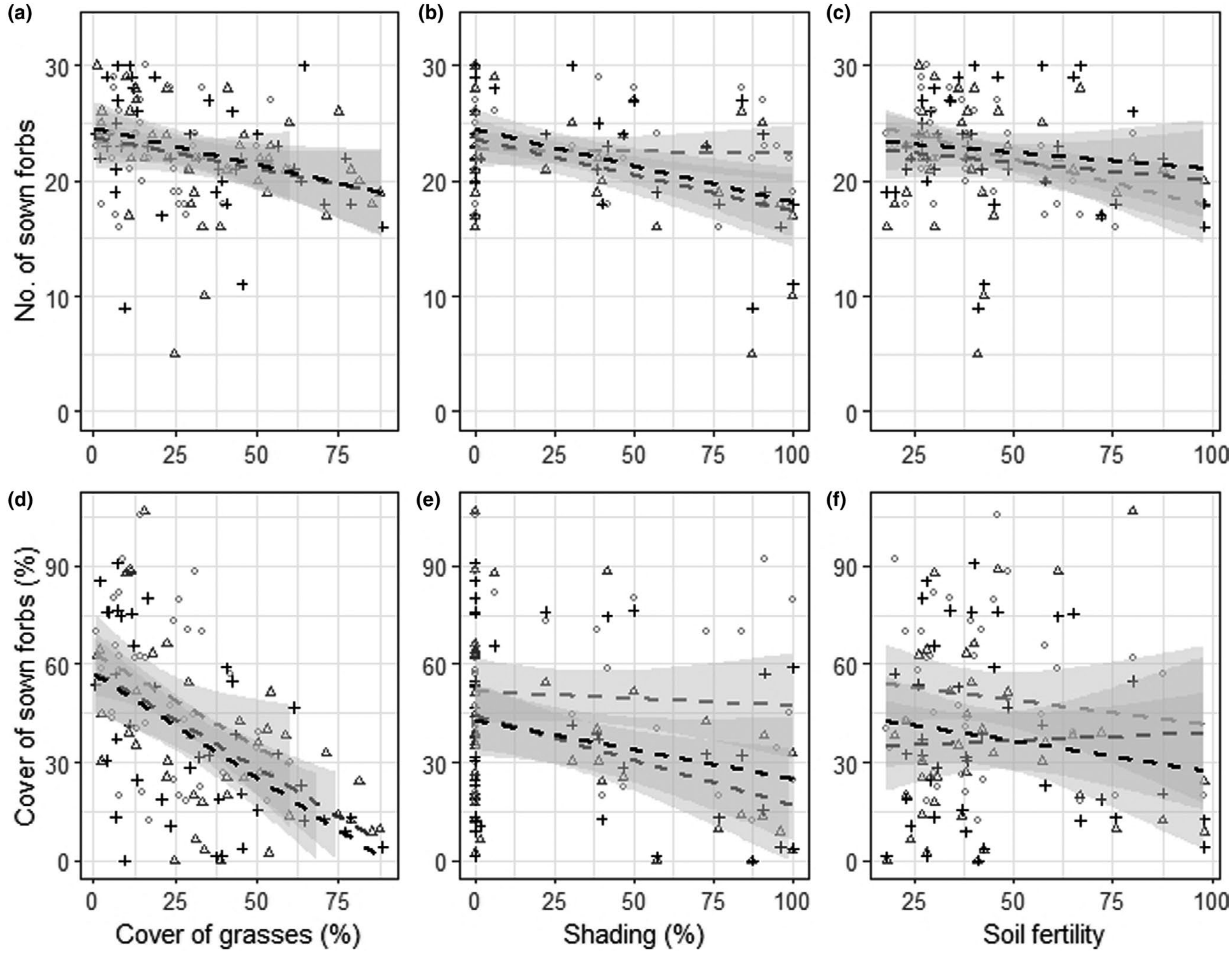


FIGURE 5 Effect of the cumulative cover of grasses (a, d), shading (b, e) and soil fertility (c, f) on the number and cover of sown species per 1,000 m² in 2017 (=dots, light grey), 2018 (=triangles, grey) and 2019 (=pluses, black)

Altogether, forb cover on WFSs reached over 60%, which is very high (see Appendix S4).

Contrary to Lepŝ et al. (2007), we found at least as many spontaneously emerging forb species as sown species on WFSs, both contributing to the high plant diversity. Thus, sowing a balanced ratio between competitive/weak and high/low growing forbs at a low sowing rate of 0.4–0.5 g/m^2 left enough gaps for desired spontaneous forbs, also reducing the cost of the seed mixture considerably. The higher dissimilarity of spontaneous forb communities was mainly caused by species turnover, with beta diversity and turnover component decreasing with time, indicating the change from annual (e.g. *Filago arvensis*) to perennial (e.g. *Euphorbia cyparissias*) spontaneous forb communities. As a result of the extreme drought in 2018 and 2019, however, some annuals reappeared in vegetation gaps in 2019. Overall, the cover of spontaneous forb species was comparatively low. Weedy forbs became dominant only on very few WFSs (Figure S4). In contrast to grass-dominated sites, however, these WFSs still provided abundant nectar and pollen. The cover of spontaneous forbs remained relatively stable with regard to all investigated environmental factors.

Altogether, shading negatively affected sown forbs most. On heavily shaded areas, only a few sown species, such as *A. millefolium* and *D. carota*, established successfully in our study. However, as many plant species in the mixtures are light-demanding species of grassland or mesophilic/thermophilic fringe communities, they are rather weak competitors to species which dominate shaded communities of nutrient-rich sites in agricultural landscapes, such as *B. sterilis* or *E. repens*. The cover of grasses increased parallel to shading, significantly reducing the cover of the sown forbs. Consequently, WFSs should not be established on north-exposed, heavily shaded field edges. For these sites, mixtures better adapted to shady conditions could be developed and applied. However, flower strips are an AES that aims to promote species of the agricultural landscape and thus of open and sunny habitats. Therefore, heavily shaded sites would only marginally benefit AES target species, if at all (Schmidt et al., 2022).

The dominance of competitive grasses can considerably reduce the cover of sown forbs (Haaland et al., 2011). Grasses probably emerged from the soil seedbank, migrated from neighbouring vegetation or may already have been present due to insufficient seedbed

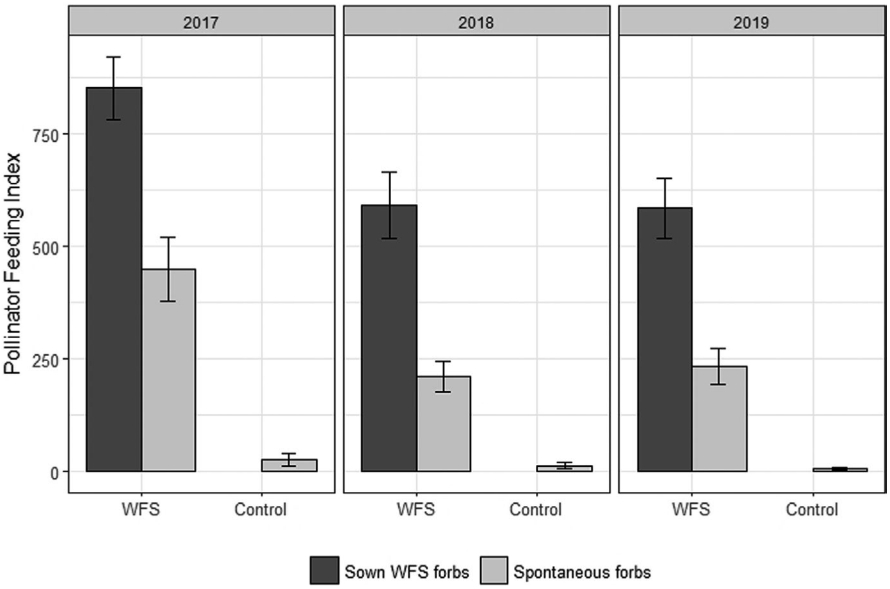


FIGURE 6 Mean Pollinator Feeding Index (±*SE*) of sown and spontaneously established forbs on wildflower strips (WFS) or control cereal fields in 2017, 2018 and 2019

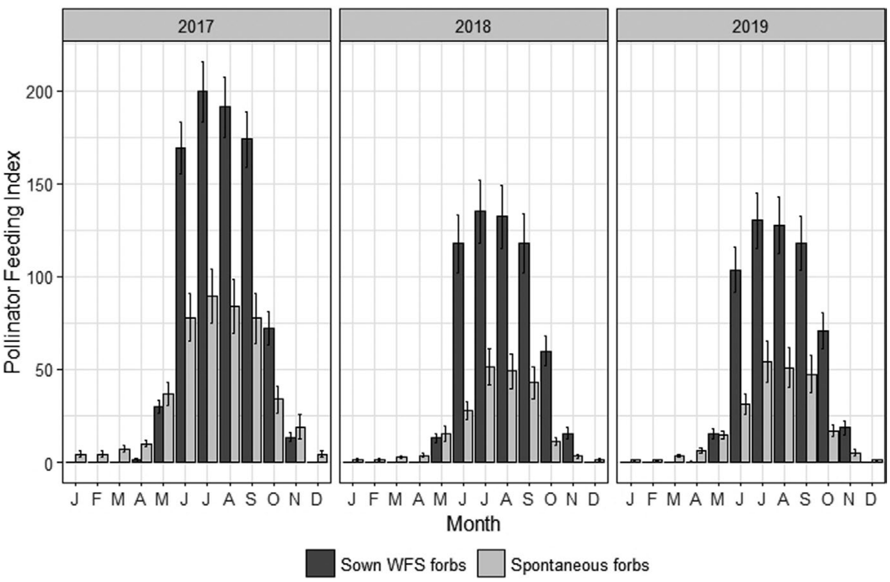


FIGURE 7 Monthly distribution of the mean Pollinator Feeding Index (±*SE*) of sown and spontaneously established forbs on wildflower strips in 2017, 2018 and 2019

preparation. They have an ecological function, for example, as host plants for some pre-imaginal butterfly stages, but grass seeds are usually still sufficiently present in the remaining semi-natural landscape structures. Thus, although it is common practice in other countries (Piqueray et al., 2019), grasses should not be included in WFS seed mixtures. When grass cover was high in the first year of the study, it was also high in the following years, confirming the findings of Weidlich et al. (2018), and indicating the importance of early established sown forbs to counteract grass dominance.

Measures to promote biodiversity are particularly necessary in highly productive landscapes (Haenke et al., 2009), where semi-natural habitats are rare due to intensive agricultural use. In our study, sites with a higher soil fertility had a lower, but still high species richness of sown forbs. Weed pressure is known to be higher on fertile soils (Piqueray et al., 2019), but our study shows that by using site-adapted native seed mixtures, WFSs can be established successfully on poor as well as on highly productive soils.

Overall, landscape effects played only a minor role compared to plot-level factors explaining plant composition at all scale levels, and relationships were often not consistent neither between years nor along a gradient of landscape levels (but see Appendix S3 for conditional averaged model estimates and Figures S3, S5 and S7). We expected that a high habitat diversity would provide a higher plant species pool and that a higher spatial connectivity to open habitats and other WFSs would presumably lead to an enhanced exchange of diaspores by wildlife, agricultural machinery or wind (Zonneveld, 1995). Although not confirmed by the full averaged model estimates, we found a trend that open habitats had differing effects on forb cover, depending on shading at the 250 m scale level or proportion of WFS at the 500 m scale level and soil fertility at the 1,000 m scale level. Furthermore, the cover of grasses increased less on WFSs with a high habitat diversity at higher scale levels over time. Possibly, the WFS lifetime of 5 years is too short to observe an approximation to the plant species pool at landscape level. However, we studied only plants as sessile organisms and local seed banks may play a more important role in the first colonisation period. For more mobile animal species groups, studies have found effects of landscape structure on the ecological effectiveness of WFSs (Haenke et al., 2009; Hellwig et al., 2022; Schmidt et al., 2022).

In our study, grass cover and shading had a decisive effect on the performance of perennial WFSs. Dispersion in the data, however, indicates other unverifiable processes, for example farmers' disregard of recommended practices in terms of seedbed preparation, seed application or management. As the WFS selection in our study was random and anonymous, documentation of implementation and management was not possible, and these effects could not be included in our statistical analyses.

4.3 | Expected benefits for pollinators (Pollinator Feeding Index)

According to our newly developed PFI, sown native species with potentially high pollen and/or nectar production contributed most to the food supply for pollinating insects on WFSs. Large amount of pollen and nectar, especially during the main flying time in summer, would lead to a clear preference of pollinators visiting WFSs, as flower cover is positively related to the absolute number of insect species (Ouvrard & Jacquemart, 2018; Warzecha et al., 2018). Plant species with high PFI values, like *C. jacea*, *T. pratense* and *Knautia arvensis*, were also found to be of high relevance for insects in other field studies (Haaland & Gyllin, 2010; Wood et al., 2017). Nevertheless, species with lower PFI values, like *Campanula rotundifolia*, can provide important pollen resources for oligolectic insects. Hence, a high plant and functional group diversity is associated with a higher availability of floral resources over time and different morphological adaptions of the fauna (Balzan et al., 2014; Wix et al., 2019).

In our study, spontaneously established forbs accounted for one quarter to one third of the potential total pollen and nectar food provision, particularly species flowering in early spring like *Draba verna* or *Veronica* spp., and thus, probably also supported the local pollinator community, as shown by Warzecha et al. (2018). Spontaneous forbs can comprise a large amount of the wild bee pollen diet over the whole vegetation period (Ouvrard et al., 2018; Wood et al., 2017) meaning that their additional contribution to the ecological performance of the flower strip should not be underestimated (Di Pasquale et al., 2013). Thus, the evaluation of WFS performance should include the diversity of both sown and spontaneously established forbs.

The decline of the PFI from 2017 to 2018/2019 is most likely due to the general decrease in total plant cover as a result of low precipitation in 2018 and 2019 (100–200 mm below the long-term mean, German Meterological Service, 2020). However, the proportion provided by sown and spontaneously established species remained largely stable over the years, regardless of weather conditions, making the results reproducible.

The PFI was intended to improve the assessment of pollinator food supply, by weighting vegetation survey (relevé) data with plant species traits (nectar and pollen production, flowering period). A bias can arise from including plant cover (and not flower cover) recorded in a snapshot, but at the time of highest detectable species diversity. Nevertheless, statistical analysis showed that the PFI correlated strongly with the species richness and abundance of wild bees on WFSs (Schubert et al., 2021), indicating the success of this AES.

4.4 | Conclusions and management recommendations

Species-rich perennial native WFSs provided a diverse, forb-rich vegetation and related feeding resources for pollinators over the 5-year AES funding period, shaped by the good performance of the sown wildflower mixtures and a high diversity of spontaneously established forbs, which colonised gaps caused by the low sowing rate of 0.4–0.5 g/m^2. The overall high plant species richness on WFSs is suitable to support a high number of pollinator species (Wix et al., 2019), which probably provide important ecosystem services both for agriculture and nature conservation (Balzan et al., 2014). WFSs could be established successfully largely independent of the landscape context. WFS implementation, however, should be avoided in heavily shaded sites, where grasses often become dominant and AES target species are unlikely to benefit. If grasses or other weedy species occur in dense and high stands, an appropriate and especially timely management, for example mowing, is necessary as also recommended in other studies (Kirmer et al., 2018; Wix et al., 2019). To avoid failures in implementation and management of WFSs and to achieve the maximum cost–benefit ratio, advisory services for farmers are necessary, as already practised in some EU countries (Leventon et al., 2017).

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTIONS

A.S. contributed to data collection, conducted trait measurements and led the writing of the manuscript; A.S. and N.H. analysed the data; A.S., S.T. and A.K. designed the experiment; Significant inputs from S.T., A.K., K.K. and N.H. helped to interpret and critically discuss the results. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.qnk98sfj9 (Schmidt et al., 2021).

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