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Collaborative approaches at the landscape scale increase the benefits of agri-environmental measures for farmland biodiversity

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A B S T R A C T

Ecological focus areas (EFAs) are a key element of European agri-environmental measures, which aim at mitigating the negative impact of intensive agricultural practices on biodiversity. They are mostly implemented at local scale, such as action-based EFAs (prescribed minimum biodiversity-friendly management) and result-based EFAs (prescribed minimum biodiversity outcome). Implementation at the landscape scale as part of a collaborative landscape-targeted approach is less frequent. There, farmers of a given region jointly determine where and which measures are implemented in order to create a biodiversity-friendly landscape. The effectiveness of the three different, but often intertwined approaches to promote farmland biodiversity, has hardly ever been studied. To this end, we analyzed data from 121 1-km^2 squares distributed across the Swiss agricultural landscapes. At local scale (10-m^2 units), we found that plant species richness was higher in all EFA categories compared to management units outside EFAs, but tended to be highest in result-based and in collaborative landscape-targeted EFAs. At landscape scale (1-km^2 units), plant species richness was positively related to a large total area of all EFAs, while butterfly and bird richness were positively related to a large total area of all EFAs with a high share of collaborative landscape-targeted EFAs. We conclude that while result-based, and especially collaborative landscape-targeted EFAs come along with higher transaction costs, they contribute substantially to farmland biodiversity at different spatial scales.

1. Introduction

Biodiversity is declining worldwide and intensified agricultural practices are considered to be one of the major drivers of this decline (IPBES, 2019). To halt and reverse the ongoing decline of farmland biodiversity, agri-environment schemes have been introduced in many parts of the world in the 1990 s (e.g., European Union's Common Agricultural Policy reform in 1992). Due to the mixed success of those early efforts in promoting biodiversity (Kleijn et al., 2006), they have constantly been refined, for example in 2013 and in 2021 by the reforms of the European Union's Common Agricultural Policy. Ecological focus areas (EFAs) are a core element of agri-environment schemes. These are farmland management units that aim at promoting biodiversity. The detailed definition of EFA and their implementation vary depending on countries and regions (Herzon et al., 2018). To date there are three main categories of EFAs, which we refer to as action-based EFAs, result-based EFAs and collaborative landscape-targeted EFAs.

By prescribing specific, biodiversity-friendly minimum actions for local management (e.g., no use of pesticides, limited fertilization, delayed first cut, or a limitation of grazing or cuts), action-based EFAs reduce the land-use intensity locally in regions with intensive agricultural management, which primarily benefits local biodiversity (Batáry et al., 2015). Conversely, in regions where farmland is at risk of abandonment, action-based EFAs ensure an upkeep of traditional extensive farming practices and prevent scrub encroachment, thus preventing local biodiversity decline (Kampmann et al., 2008; Pornaro et al., 2013). In terms of implementation, it was found that action-based EFAs are relatively easy to apply and reward farmers largely for their efforts and possible yield losses, regardless of any increase in biodiversity. Yet, it has been discussed and questioned repeatedly whether they are effective enough for halting the ongoing loss of biodiversity (Kleijn et al., 2011). Possible reasons for insufficient effectiveness of action-based EFAs might be that the abiotic and biotic preconditions of the management units are not suitable for biodiversity (e.g. unsuitable abiotic conditions, too low or too high habitat complexity in the surroundings, a limited species pool in the landscape, or barriers that hinder species to disperse

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(Batáry et al., 2015; Boetzl et al., 2021; Geppert et al., 2020; Kleijn and van Langevelde, 2006; Knop et al., 2011, 2006; Ruas et al., 2021)). Also, management rules may not be appropriate at specific sites, e.g., the timing of the first cut of meadow EFAs (Knop et al., 2006). Farmers may lack motivation to optimize site selection and management for biodiversity benefits, as they receive their compensation payments regardless of the outcome.

Result-based EFAs aim to promote local biodiversity more effectively by ensuring that only predefined minimum outcomes related to local biodiversity are rewarded (e.g., the presence of a certain number of key indicator species (Burton and Schwarz, 2013; Elmiger et al., 2023; Fleury et al., 2015)). Farmers do not simply follow certain minimum management rules but try to restore local biodiversity, which in the best case even exceeds the required biodiversity output (Herzon et al., 2018; Matzdorf et al., 2008). However, on farms with unfavorable abiotic or biotic conditions, the biodiversity goals might not be achieved. This shifts the risk of whether the goals are achieved from the authorities to the farmers. Consequently, farmers accept the higher risk of this EFA category only if financial incentives are higher (Niskanen et al., 2021). Transaction costs are higher for result-based EFA implementation, because the farmer needs to plan and adapt the local management more carefully, and because the local biodiversity outcome needs to be checked by the authorities or by an independent specialist in order to justify the payment (O'Rourke and Finn, 2020).

Collaborative landscape-targeted EFAs focus less on local biodiversity and more on the biodiversity of the entire landscape (Landis, 2017; Pe'er et al., 2017). They aim to enhance landscape-scale biodiversity by coordinating EFA selection and placement across several farms, taking into account the preconditions and the potential of the larger landscape (McKenzie et al., 2013; Prager et al., 2012; van Dijk et al., 2015; Westerink et al., 2017). This includes creating new habitats (and thereby increasing habitat diversity), as well as connecting them in a way that allows populations to establish, propagate and disperse successfully (Resasco, 2019). However, the transaction costs are even higher than for result-based EFAs. First, the commitment of the farmers to collaborate must be obtained. Then, the status quo regarding the occurrence of certain habitat types in a landscape must be mapped in order to develop a concept that defines which and how many EFAs need to be placed, and where, and how their management needs to be adjusted to achieve the goals. This commitment and the efforts of the various actors (beyond farmers) may increase their knowledge and thus may further benefit biodiversity (Moxey and White, 2014).

Most studies investigating the effectiveness of EFAs on local-scale biodiversity (e.g. by comparing the local-scale biodiversity of EFAs with the local-scale biodiversity of sites outside EFAs) have examined action-based EFAs (Aviron et al., 2009; Batáry et al., 2015; Boetzl et al., 2021; Kleijn et al., 2006; Knop et al., 2006), while fewer evaluations have been carried out on result-based EFAs (Matzdorf and Lorenz, 2010; Zingg et al., 2019). To our knowledge, a detailed evaluation of the effectiveness of EFAs implemented in a collaborative landscape-targeted approach is missing. As a consequence, we do not currently know whether collaborative landscape-targeted EFAs are more effective in promoting local-scale biodiversity than locally implemented action-based or result-based measures.

In addition to assessing the effectiveness of different EFA management practices in promoting biodiversity at local scale, it is important to quantify the effectiveness of EFA management in promoting biodiversity at landscape scale, as this is ultimately the scale at which farmland biodiversity should be promoted by these measures. However, evaluations which show, for example, that landscape-scale biodiversity is increased by a large total area of EFAs or by specific features of EFAs that increase habitat diversity or connectivity in a landscape, are very rare (Meier et al., 2022; Zingg et al., 2019). Consequently, we currently do not know to which extent collaborative landscape-targeted EFAs (aimed at increasing habitat diversity and connectivity) contribute to EFAs positive effect on landscape biodiversity.

In this study, we therefore analyzed effects of the three categories of EFAs – action-based, result-based and collaborative landscape-targeted EFAs – in promoting (1) local-scale and (2) landscape-scale biodiversity. We conducted the study in Switzerland, where EFAs have been implemented in a tiered approach from 1993 (action-based) and 2001 (result-based, collaborative landscape-targeted) onwards. All EFAs had a minimum registration period of eight years, and the three categories of EFAs were partially intertwined, i.e. result-based EFAs had the same minimum management requirements as action-based EFAs, but could be voluntarily improved by farmers to achieve the minimum local-scale biodiversity outcome. In the case of collaborative landscape-targeted EFAs, both action-based and result-based EFAs were combined, yet the collaborative projects defined more far-reaching measures, e.g. increasing habitat connectivity and diversity, to promote specific groups of target species in that landscape. The detailed descriptions of the different EFA types in the three categories as well as the corresponding measures are listed in the Supplementary Table S1. We asked the following research questions: (1a) Do EFAs (any category) harbor a higher local-scale plant diversity compared to management units outside EFAs (i.e., non-EFAs), and (1b) which combination of the three EFA categories results in the highest local-scale plant diversity? (2a) Does an increasing total area of EFAs from all categories increase landscape-scale plant, butterfly and bird species richness, and (2b) is this effect increased by an increasing share of collaborative landscape-targeted EFAs? To answer these questions, we used the extensive dataset of the 'Swiss farmland biodiversity monitoring program' (www.allema.ch) on vascular plants, butterflies and birds collected in the farmland of 121 1-km^2 squares that were distributed across the strong gradients of topography, climate and land use in Switzerland. In those 1-km^2 squares, management units with no, action-based, result-based and/or collaborative landscape-targeted EFAs were investigated, which we examined together with topographic, climatic and land-use variables for their effects on biodiversity.

2. Material and methods

2.1. Study area

The study area was the farmland (i.e., utilized agricultural area, UAA) of Switzerland, which covers ~10000 km^2 (Fig. 1). It extends from the Swiss lowlands (approximately 300 m a. s. l.) to mountain farmland in and along the central Alps and Jura mountains (approximately 1500 m a. s. l., 45°81N – 47°81N, 5°57E – 10°49E). North of the Alps, the climate is moist and maritime. In the interior Alpine valleys, the climate is drier and more continental, whereas the climate south of the Alps is mild and humid.

Within the study area, data were collected in 121 1-km^2 squares distributed across a large gradient of topographic, climatic and land-use conditions in a stratified sampling design (Ecker et al., 2023) (Fig. 1). Within the 1-km^2 squares, we only investigated the farmland, i.e., data from forests, settlements, water bodies, glaciers, rocks and alpine summer pastures were excluded from all analyses.

2.2. Species data and richness metrics at local and landscape scales

Species data on plants, butterflies and birds were sampled from 2015 to 2019 in the farmland of the 1-km^2 squares (Fig. 1). The 1-km^2 squares were randomly assigned to five groups and the groups were sampled in five subsequent years. For all three taxa, the sampling was done in the same year.

Plant species were sampled in circles of 10 m^2 once at the peak of flowering in the year of survey and their respective cover was estimated in cover classes for the whole circles (Braun Blanquet). In order to make the field effort plannable, per 1-km^2 square 18 ± 2.2 (mean ± SD; min=2, max=19) sampling sites were selected in the farmland (from a regular grid of 50 m × 50 m) in as many different vegetation types as

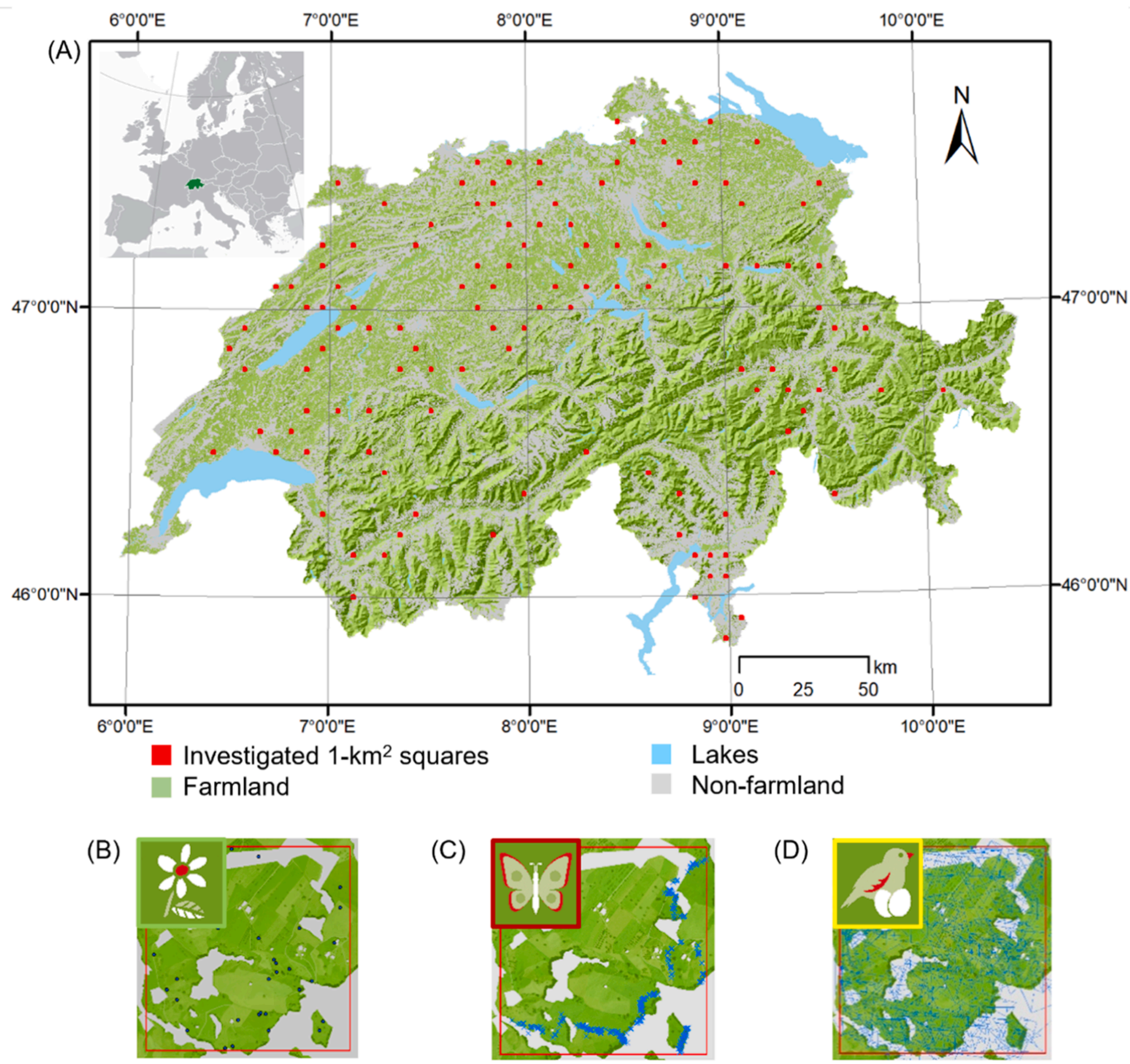

Fig. 1. (A) Location of the study area within Europe and the 121 investigated 1-km^2 squares within the study area. (B-D) Exemplary 1-km^2 square with locations of sampling sites for plants (circles of 10-m^2) (B), butterfly transects (C), and bird territories (D).

possible, and 12 ± 3.1 (min=1, max=14) additional sampling sites were selected in as many different EFA types as possible (for a detailed description of the sampling design see Ecker et al., 2023; Fig. 1). An overview of the sampled EFA types and the main vegetation types is given in Supplementary Table S2. The sample sites outside of EFAs belonged to various vegetation types, mainly dominated by Medio-European lowland hay meadows and field crops. For the analysis at local scale, we counted the observed number of plant species per 10-m^2 plot, while for the analysis at landscape scale, we counted the observed number of plant species across all 10-m^2 plots in the farmland of each 1-km^2 square.

Data on butterfly species (Fig. 1) originated from the 'Swiss Biodiversity Monitoring' (Fig. 1; www.biodiversitymonitoring.ch). Butterflies were surveyed seven times between April and September in the respective year along a 2.5 km transect per 1-km^2 square that had to be walked at a constant speed. The transect was defined in advance on the respective map to represent the 1-km^2 square. Transect walks were conducted between 10 a. m. to 5 p. m. during favorable weather conditions regarding wind, temperature and sunshine. The identity of all observed butterfly species and the coordinates of their position were recorded. For the landscape-scale analyses, we considered the number of species per 1-km^2 square of all butterflies that occurred in farmland. This resulted in a mean transect length of 1784 ± 596 m (mean ± SD).

Bird data (Fig. 1) were obtained from the common breeding bird survey of the Swiss Ornithological Institute (www.vogelwarte.ch). They were sampled three times between April and July in the respective year of survey across the entire 1-km^2 square for a constant time. The length of the walked way was in general 3 – 5 km, walking time per km was 45 min on average. Weather conditions had to be appropriate (i. e. maximal windspeed of Beaufort 3, no strong rainfall, snow or fog). Birds were sampled in the morning, not later than 11 a. m. The ornithologists delineated the breeding bird territories and indicated the species and number of individuals per territory based on their field observations. For landscape-scale analyses, we considered the number of species per 1-km^2 square of all observed birds, which had the centroid of their breeding territory in farmland.

2.3. Data on ecological focus areas and environmental factors

The Swiss EFAs were all subject to specific, biodiversity-friendly minimum actions for local management (Table S1). In a tiered approach, farmers can further optimize this management. If a minimum number of indicator plants indicating high plant species richness occur in meadows and/or ecological structures occur in pastures and fruit orchards (Fig. 2), the respective management unit is "upgraded" from action-based EFA to result-based EFA and qualifies for a premium payment (BLW, 2013). Further, if action- or result-based EFAs are targeted to the specific landscape through additional specific measures and are planned with the involvement of a group of farmers, they qualify as collaborative landscape-targeted EFAs and additional subsidies are granted (BLW, 2013; Fig. 2).

Generally, the Swiss agri-environment scheme prescribes the management of EFAs depending on the present land-use type, which between 2015 and 2019 resulted in 15 different types of EFAs, such as low intensity meadows, low intensity pastures, wildflower strips and hedges (BLW, 2013; and see Table S1). In the 121 1-km^2 squares studied, 11.0 ± 10.4 % (mean ± SD) of the farmland were managed as EFAs. Of these, result-based EFAs accounted for 42.3 ± 44.7 %, and collaborative landscape-targeted EFAs accounted for 62.8 ± 57.9 %, with much of the result-based EFAs (73.6 ± 65.6 %) overlapping with the collaborative landscape-targeted EFAs (Fig. 2).

As the three EFA categories were intertwined, we investigated the local-scale plant species richness in the following combinations of the three EFA categories: action-based EFAs (i.e., not additionally result-based and/or collaborative landscape-targeted; 513 plots in 96 squares), result-based EFAs (i.e., not additionally collaborative landscape-targeted; 191 plots in 48 squares), collaborative landscape-targeted action-based EFAs (632 plots in 101 squares) and in collaborative landscape-targeted result-based EFAs (446 plots in 90 squares). As a control we selected management units outside EFAs, i.e., non-EFAs (1756 plots in all 121 squares). In terms of variables for the landscape-scale models, we estimated the total area of all EFAs and the share of all collaborative landscape-targeted EFAs in relation to all EFAs in a landscape (Table 1). The cantonal authorities provided polygon data on type, category, location and extent of EFAs in the 1-km^2 squares (positional accuracy approx. 2 m).

As not only EFAs but also environmental factors are relevant for plant and animal distribution patterns in agricultural landscapes, we included environmental variables in the models in addition to the EFA variables (Table 1). To represent topography, we used slope and northness (i.e., cosine of aspect), calculated from a digital elevation model with 25 m x 25 m resolution (Swisstopo, 2005). To represent climate, we used the yearly precipitation days and annual degree-days applying a 0°C threshold, calculated from downscaled monthly precipitation and temperature maps of the current climate (1950–2000, 25 m x 25 m resolution; Guisan et al., 2007; Hijmans et al., 2005; Zimmermann and Kienast, 1999). As farmland was not the same size in all 1-km^2 squares, we controlled for the species/habitat-area relationship by taking into account the total area of farmland in the 1-km^2 squares, which we approximated by excluding forests, settlements, water bodies, glaciers, rocks and alpine summer pastures (Swisstopo, 2021).

Table 1
Variables included in models for explaining biodiversity on local scale (10-m^2 plots) and on landscape scale (farmland in 1-km^2 squares).

Variable	Unit	Mean +- SD Local scale	Mean +- SD Landscape scale
Plant species richness		24.02 ± 11.76	137.21 ± 38.20
Butterfly species richness			33.64 ± 14.68
Bird species richness			33.71 ± 8.13
EFA area	m^2		73,868.25 ± 60,480.39
% collaborative landscape-targeted EFAs on EFA area	%		0.62 ± 0.33
EFA category (none, action-based, result-based, collaborative landscape-targeted action-based, collaborative landscape-targeted result-based)		(factor)	
Northness	°	-0.01 ± 0.71	0.00 ± 0.06
Slope	°	11.80 ± 8.68	11.21 ± 7.09
Annual degree days	°C d	27,726.98 ± 5642.42	27,799.22 ± 5710.02
Yearly precipitation days	d	36.19 ± 4.03	36.14 ± 4.05
Farmland area	m^2		678,497.40 ± 204,838.90

For local-scale analyses, we extracted the values of the environmental factors for all 10-m^2 plots with plant species richness data, and for the landscape-scale analyses, we calculated the mean values of the environmental factors within the entire farmland per 1-km^2 square.

We checked all explanatory variables (Table 1) for multicollinearity. Their correlation factor was always below 0.5 (see Supplementary Table S3a and S3b) and the Variance Inflation Factors did not exceed 2.5 (Chatterjee and Hadi, 2006; Neter et al., 1983). Thus, all variables were retained for the models. All variables were processed and tested for multicollinearity using R version 4.2.2 (R Core Team, 2022) and ArcGIS pro version 3.0.3 (ESRI, 2022).

2.4. Data analysis

At the local scale, we analyzed the effects of the EFA categories (i.e., none, action-based, result-based, collaborative landscape-targeted

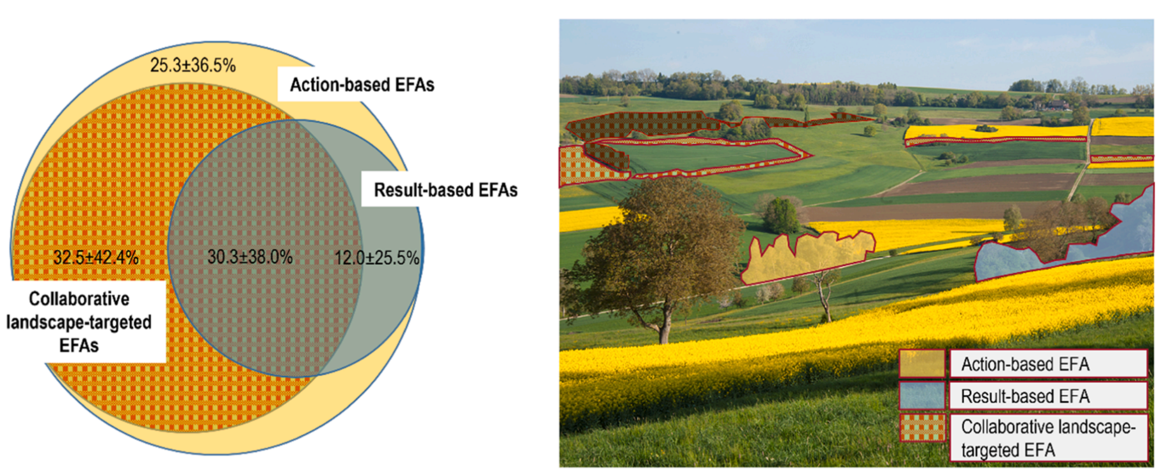

Fig. 2. Implementation of EFAs in Switzerland. All EFAs are subject to prescribed management restrictions, i.e., are action-based EFAs (yellow). Additionally, they can be registered as result-based EFAs if certain criteria (e.g., presence of indicator species or the occurrence of ecological structures) are met (blue), and/or as collaborative landscape-targeted EFAs if they are targeted to the specific landscape and involving a group of farmers (checkered). The percentages represent the shares (mean ± SD) of the combinations of the three EFA categories in the total of all EFAs in the study area (i.e., 11.0 ± 10.4 % of the farmland).

action-based and collaborative landscape-targeted result-based) and environmental factors on local-scale plant species richness by using a linear mixed model (R-library "lmer"). Normality and homogeneity of the residuals were visually checked using QQ plots and the graph of residuals versus fitted values. We standardized the explanatory variables with the exception of the EFA category (i.e., northness, slope, annual degree days, and yearly precipitation days; Table 1) as magnitudes of their standard deviation. We included the '1-km^2 square' as random intercept to account for potential non-independence of individual samples within each 1-km^2 square (Bates et al., 2014). Model quality was assessed based on the marginal and the conditional pseudo R^2, which were calculated with R-library "piecewiseSEM" version 2.1.2 (Lefcheck, 2016). Differences among EFA categories were tested with the R-library "emmeans" version 1.8.8 (Searle et al., 1980).

At the landscape scale, we investigated the effect of EFAs (i.e., total EFA area and share of collaborative landscape-targeted EFAs on total EFA area) on landscape-scale biodiversity by using generalized linear models with a Poisson distribution. Homogeneity of the residuals were visually checked using the graph of residuals versus fitted values. We used the landscape-scale species richness of plants, butterflies and birds as respective response variables in the model and related it to the explanatory variables (i.e., northness, slope, annual degree days, yearly precipitation days, farmland area and interaction term between total EFA area and share of collaborative landscape-targeted EFAs on total EFA area; Table 1). The response variables were tested for spatial autocorrelation using the Moran's I procedure. All values of Moran's I were positive and lower than 0.5. Therefore, no correction for spatial autocorrelation was included in the models. The explanatory variables were standardized as magnitudes of their standard deviation in order to obtain standardized coefficients and were included in the models as linear terms.

All statistical analyses were performed using R version 4.2.2 (R Core Team, 2022).

3. Results

3.1. Effects on local-scale plant species richness

Model quality of the local-scale model was reasonable (marginal pseudo $R^2 = 0.33$, conditional pseudo $R^2 = 0.46$). Generally, plant species richness at local scale (i.e., in circles of 10-m^2) was significantly higher within EFAs than outside EFAs (Fig. 3A and Table S2; all $P < 0.001$). Further, plant species richness was significantly higher in collaborative landscape-targeted result-based EFAs than in action-based EFAs ($P < 0.001$; Fig. 3A and Supplementary Table S4a and S4b) and collaborative landscape-targeted action-based EFAs ($P = 0.004$; Fig. 3A and Supplementary Table S4a and S4b). Thus, in general, local-scale plant species richness tended to be higher for result-based EFAs than for action-based EFAs, and for collaborative landscape-targeted EFAs than for non-collaborative-landscape-targeted EFAs, and highest for the combination of result-based and landscape-targeted EFAs (Fig. 3A and Supplementary Table S4a and S4b).

In addition, especially a locally steep slope and fewer annual degree days, but slightly also south-facing slopes and decreasing yearly precipitation days were beneficial for local-scale plant species richness (Fig. 3B and Supplementary Table S4a and S4b).

3.2. Effects on landscape-scale plant, butterfly and bird species richness

Model quality of the landscape-scale models was reasonable (plants: $R^2 = 0.45$, butterflies: $R^2 = 0.65$, birds: $R^2 = 0.27$). At landscape scale, plant species richness was positively related to the total area of all EFAs ($P < 0.001$; Fig. 4A and Supplementary Table S5), while butterfly species tended to be ($P = 0.055$; Fig. 4A and Supplementary Table S5) and bird species richness was significantly ($P = 0.047$; Fig. 4A and Supplementary Table S5) positively related to the total area of all EFAs with a large share of collaborative landscape-targeted EFAs.

In addition, a steep slope, as well as few annual degree days and few yearly precipitation days were positively related to landscape-scale plant and butterfly species richness in particular, but also tended to be positively related to the landscape-scale species richness of birds (Fig. 4B

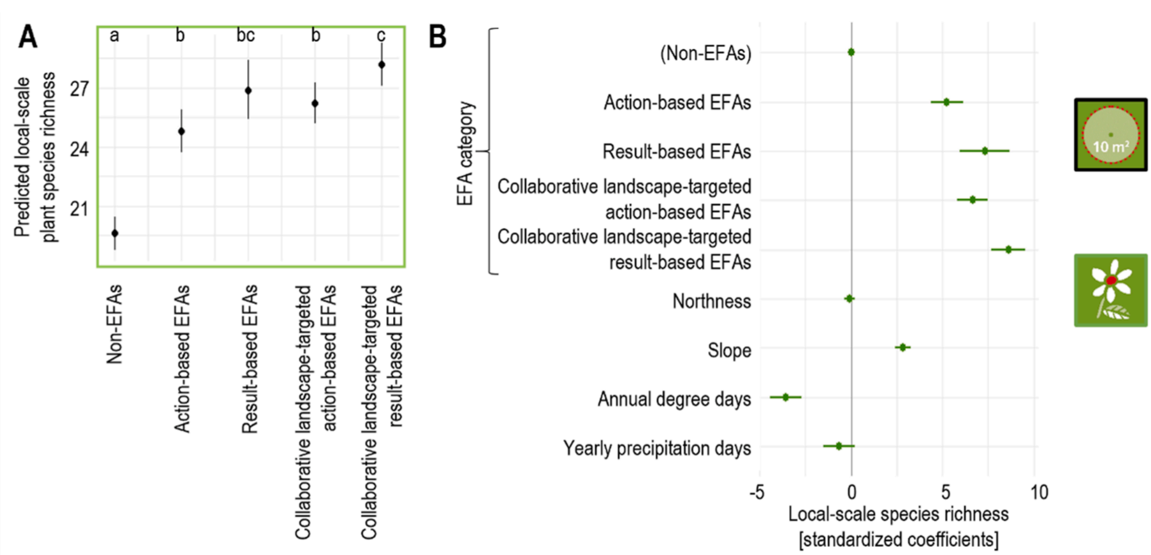

Fig. 3. (A) Predicted plant species richness at local scale (i.e., in circles of 10-m^2) in non-EFAs ($n_{samples}$=1756, $n_{squares}$=121), in action-based EFAs (i.e., not additionally result-based or collaborative landscape-targeted; $n_{samples}$=513, $n_{squares}$=96), in result-based EFAs (i.e., not additionally collaborative landscape-targeted; $n_{samples}$=191, $n_{squares}$=48), in collaborative landscape-targeted action-based EFAs ($n_{samples}$=632, $n_{squares}$=101), and in collaborative landscape-targeted result-based EFAs ($n_{samples}$=466, $n_{squares}$=90). P < 0.001 for differences between groups. Non-EFAs were significantly different from all EFA categories, while collaborative landscape-targeted result-based EFAs were further significantly different form action-based EFAs and collaborative landscape-targeted action-based EFAs. (B) Standardized coefficients on effects of the local-scale EFA category and local-scale environmental factors on local-scale plant species richness. The first factor level (i.e., non-EFAs) defines the reference. Whiskers span the 95 % confidence interval. A table of the results can be found in the Supplementary Table S4a and S4b.

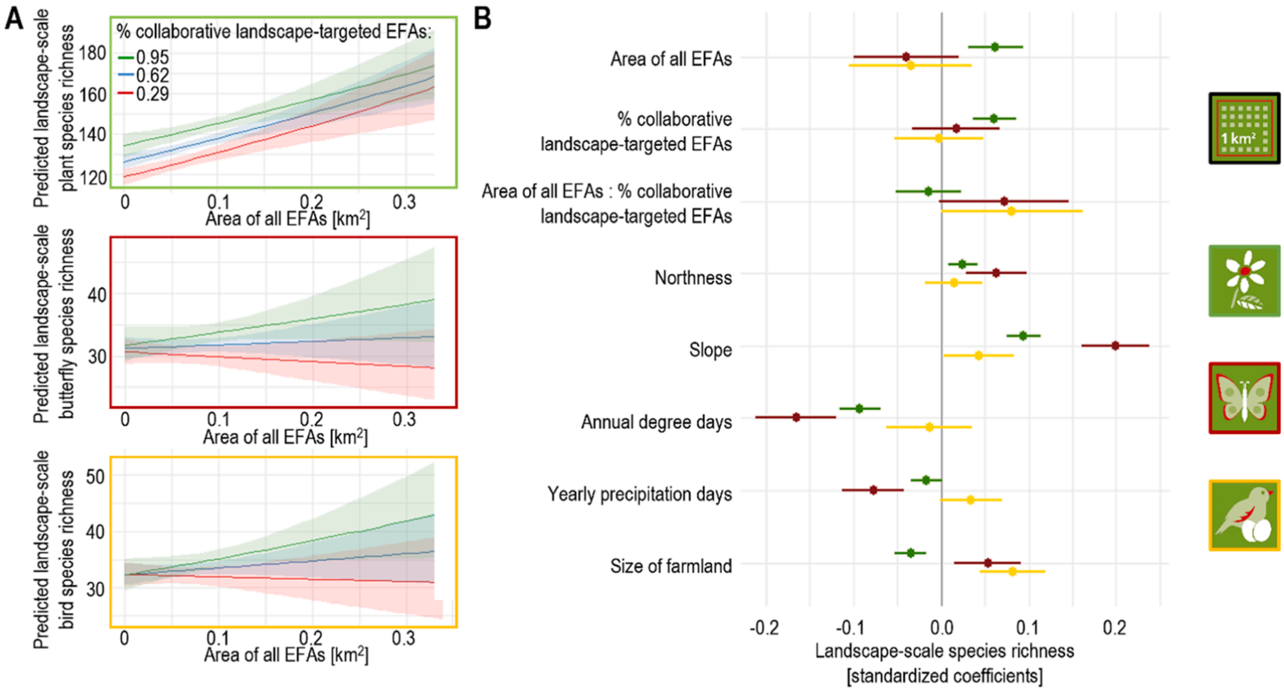

Fig. 4. (A) Predicted landscape-scale species richness (farmland in 1-km^2 squares; $n_{squares}$=121) of plants, butterflies and birds with an increasing area of EFAs at three percentages of collaborative landscape-targeted EFAs. (B) Standardized coefficients of EFA variables and landscape-scale environmental factors on landscape-scale species richness of plants (green), butterflies (red) and birds (yellow). The shaded bands or whiskers show the 95 % confidence interval. A table of the results can be found in the supplementary Table S5.

and Supplementary Table S5). Further, total size of farmland was positively related to butterfly and bird species richness, while it was negatively related to plant species richness (Fig. 4B and Supplementary Table S5).

4. Discussion

This study evaluated whether EFAs are beneficial for biodiversity and if result-based and collaborative landscape-targeted EFAs contribute more to biodiversity than action-based EFAs. Results showed that collaborative landscape-targeted EFAs in combination with result-based EFAs had the highest local-scale plant species richness, and that a high share of collaborative landscape-targeted EFAs increased the positive relationship of a large total EFA area to landscape-scale species richness, especially for birds, but – as a tendency – also for butterflies.

4.1. Local-scale plant species richness benefited from EFAs

Local EFA management had a direct effect on local-scale plant species richness, i.e., local-scale plant species richness was clearly enhanced under any of the EFA categories compared to management units outside EFAs. This is in line with numerous focal-patch studies (Aviron et al., 2009; Batáry et al., 2015; Boetzl et al., 2021; Kleijn et al., 2006; Knop et al., 2006). The reason for this locally increased plant species richness thus appears to be the minimal biodiversity-friendly management regime (e.g., a lower nutrient input; Kleijn et al., 2009).

Further, our results showed that with respect to the different EFA categories, local-scale plant species richness tended to be generally higher in result-based and in collaborative landscape-targeted EFAs than in action-based and in non-landscape targeted EFAs, and that these effects were cumulative, i.e. richness was highest in collaborative landscape-targeted result-based EFAs. Several factors might explain these findings, such as management and site selection.

Compared to action-based EFAs, where biodiversity outcomes are not verified, in result-based EFAs, where farmers were compensated for biodiversity outcomes, management and site selection appear to have gone beyond the minimum requirements in many cases. In action-based EFA meadows, for example, the minimum requirement in terms of mowing is a delayed first cut (i.e., not earlier than a fixed date depending on elevation), but the number of cuts and the height of cut are not prescribed. However, the level of local biodiversity depends not only on the timing of the first cut, but on the overall mowing regime (Klink et al., 2019). In terms of site selection, it appears that farmers have more often established result-based EFAs, based on their long-term experience, where the preconditions are more favorable for biodiversity, compared to action-based EFAs (Batáry et al., 2015; Boetzl et al., 2021; Geppert et al., 2020; Kleijn and van Langevelde, 2006; Knop et al., 2011, 2006; Matzdorf et al., 2008; Ruas et al., 2021). For example, less productive sites, i.e. steep slopes, unproductive soils, near water and near woody plants (Paulus et al., 2022; Ravetto Enri et al., 2020), may be more favorable for biodiversity than more productive sites, which may have higher nutrient levels and smaller seed banks due to more intensive previous use (e.g. wildflower strips along crops). However, as the improvements in management and site selection of result-based EFAs were based on farmers' current knowledge, opportunities and personal commitment towards safeguarding biodiversity, and as the sample size was lower, this might explain the higher variability on local-scale plant species richness of results-based EFAs compared to action-based EFAs. This might have contributed to the lack of a marked difference in local-scale plant species richness between action-based and result-based EFAs.

The tendentially higher richness of local plant species in collaborative landscape-targeted EFAs may be explained by the farmers' broader collaborative knowledge about management and site selection, and by the more careful planning of measures across landscapes, in many cases involving an ecologist giving advice to participating farmers. Also, all collaborative projects are subject to a quality check by the authorities. As a result, many plants that spread very slowly and usually over short distances were more likely to reach these areas from other nearby semi-natural areas within the farmland (Fahrig et al., 2011; Grass et al., 2021;

Zambrano et al., 2019) and persisted thanks to optimal preconditions and management. Moreover, this seems to have had a positive effect not only on the specific target species (flora and fauna), but also on other species that benefited from their promotion (i.e. the target species acted as umbrella species), and thus, on the overall plant species richness.

The local management can have an effect on local-scale biodiversity, as shown previously (Batáry et al., 2020; Bretagnolle et al., 2019; Concepción et al., 2012; Díaz and Concepción, 2016; Marja et al., 2022). Our results demonstrate the importance of establishing result-based units in an integrated landscape approach, as this also seems to help selecting the most suitable habitat patches in accessible locations and manage them in a biodiversity-friendly way to reduce local plant species loss.

4.2. At landscape scale butterfly and bird species benefitted more form high shares of collaborative landscape-targeted EFAs than plant species

Landscape-scale plant species richness increased with an increasing total area of EFAs, while landscape-scale butterfly and bird species richness increased with an increasing total area of EFAs that were part of collaborative landscape-targeted programs.

A larger total area of EFAs was beneficial to landscape-scale plant species richness, possibly because at landscape scale especially smaller organisms behave according to the relationships between species, habitat diversity and area (Connor and McCoy, 1979) and between species, habitat area and connectivity (Fahrig, 2017). However, in contrast to the positive effects of collaborative landscape-targeted EFAs on local-scale plant species richness, collaborative landscape-targeted EFAs did not enhance the positive effect of a larger total area of EFAs on landscape-scale plant species richness. This may be because plants do not migrate as quickly and as far as butterflies and birds, which reduces any additional migration from outside the farmland into the farmland despite an increasing share of collaborative landscape-targeted EFAs. As a consequence, overall species richness of plants at landscape scale (in contrast to fauna) was not further increased.

Bird species richness at the landscape scale and, to a lesser extent, butterfly species richness at the landscape scale, were related to a larger total area of EFAs with larger shares of collaborative landscape-targeted EFAs. This may be because collaborative landscape-targeted EFAs aim at increasing habitat connectivity, which may increase cross-habitat spill-over within and from outside farmland (Albrecht et al., 2010; Tscharntke et al., 2012). Also, they aim at increasing habitat diversity, which has been shown to be critical for high biodiversity at the landscape scale, because different habitats may provide different niches and thereby support different species (Ben-Hur and Kadmon, 2020; Meier et al., 2022; Smith et al., 2022). Further, for mobile species, different habitats may provide complementary resources during different stages of their life cycle (Tscharntke et al., 2012; Weibull et al., 2003). Although this study cannot exclude the possibility that collaborative landscape-targeted EFAs were implemented in previously more species-rich landscapes, we assume that the higher butterfly and bird species richness in such landscapes was mainly caused by the EFAs: The implementation of collaborative landscape-targeted EFAs usually depends mainly on a few proactive individuals who can convince others to join them and participate in projects to implement collaborative landscape-targeted EFAs, rather than on the conditions in the landscape.

Although EFAs and semi-natural habitats are not necessarily identical, the relationship of collaborative landscape-targeted EFAs and biodiversity are in line with various studies that have investigated the relationship of semi-natural habitats and biodiversity in agricultural landscapes (Aavik and Liira, 2009; Billeter et al., 2008; Jeanneret et al., 2021). From these studies, it was concluded that more than 20 % of the agricultural landscape should be covered by semi-natural habitats in order to ensure sufficient connectivity between the individual semi-natural habitats (Tscharntke et al., 2021). Although we cannot derive such thresholds here, we nevertheless show that the benefits of EFAs are not only related to their total area in the landscape, but also to the design of the EFAs, i.e. if EFAs are established in the context of collaborative landscape-targeted frameworks, the benefits of a given area of EFAs can be increased.

4.3. Negative effects of farming conditions on local- and landscape-scale biodiversity

Environmental conditions were crucial for species richness at both, local and landscape scales. Species richness was strongly increased on steep slopes, by fewer annual degree days and low annual precipitation, and to a lesser extent on south facing slopes. In addition to the physiological effect of south-facing slopes, the effect of the other environmental factors could be mainly related to land-use intensity, which is reduced under these conditions, and which in turn favors biodiversity (Meier et al., 2020).

A topographical exposure to the south leads to longer and more intensive insolation and thus affects the microclimate (Holland and Steyn, 1975), which is not only important for ectothermic taxa such as plants and butterflies, but also for endothermic taxa such as birds.

Flat farmland favors the use of farm machinery, while warm and wet climate increase yield potential. The higher land-use intensity under such conditions has a negative impact on biodiversity, on the one hand directly, e.g. through increased inputs, and on the other indirectly, by decreasing habitat diversity (Meier et al., 2022). These strong effects of abiotic conditions underline how important it is for the conservation of biodiversity to consider also the abiotic conditions and the associated land-use intensity on farmland, particularly in light of a changing climate. In collaborative landscape-targeted approaches, farmers and planners are more likely to take this into consideration.

As only farmland was included in the analyses (i.e. excluding forests, settlements, water bodies, glaciers, rocks and alpine pastures, but including, for example, less productive grassland or small woody elements), the area assessed per 1 km^2-square was not always the same. Therefore, we used the farmland area as a co-variate to control for the relationship between species, habitat area and habitat richness. Total butterfly and bird richness on farmland was positively related to farmland area, as expected, while total plant species richness was negatively related. This may be because, as faunal species, also plants depend on spillover from nearby (semi-)natural habitats, as not all agricultural management units provide suitable habitat throughout the year (Meier et al., 2022). However, in landscapes with predominantly arable land and therefore fewer nearby (semi-)natural habitats, plants, unlike butterflies and birds, have not been able to spread as quickly into farmland and their richness may therefore show a negative relationship with increasing total area of farmland.

5. Conclusion

Our results show that all EFAs maintain local-scale plant species richness better compared to the rest of the farmland, and that result-based and collaborative landscape-targeted EFAs tend to be more effective than action-based EFA. Further, to mitigate biodiversity loss at landscape scale, not only a large total area of all EFAs is important, but also, particularly for the fauna, this area should have a high share of collaborative landscape-targeted EFAs. Although more research is needed on different groups of organisms, as the groups studied do not represent the whole of biodiversity, our results suggest that, notwithstanding the higher transaction costs that result-based and collaborative landscape-targeted EFAs entail, they help to protect biodiversity at different spatial scales. Our findings thus underline recent calls for an urgent concerted action to fundamentally redesign agricultural landscapes to prevent a further loss of ecosystem services due to landscape simplification (Grass et al., 2021; Landis, 2017; Leventon et al., 2017; Petit and Landis, 2023; Petřík et al., 2015; Tscharntke et al., 2021). However, we not only support the existing calls for a paradigm shift in agriculture from local measures to a landscape design, but also call for a more careful implementation of EFAs through both result-based and collaborative landscape-targeted approaches to conserve as many organism groups as possible.

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CRediT authorship contribution statement

Felix Herzog: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Gisela Lüscher:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Eliane Seraina Meier:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Eva Knop:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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Declaration of competing interest

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

Appendix A. Supporting information

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.agee.2024.108948.

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